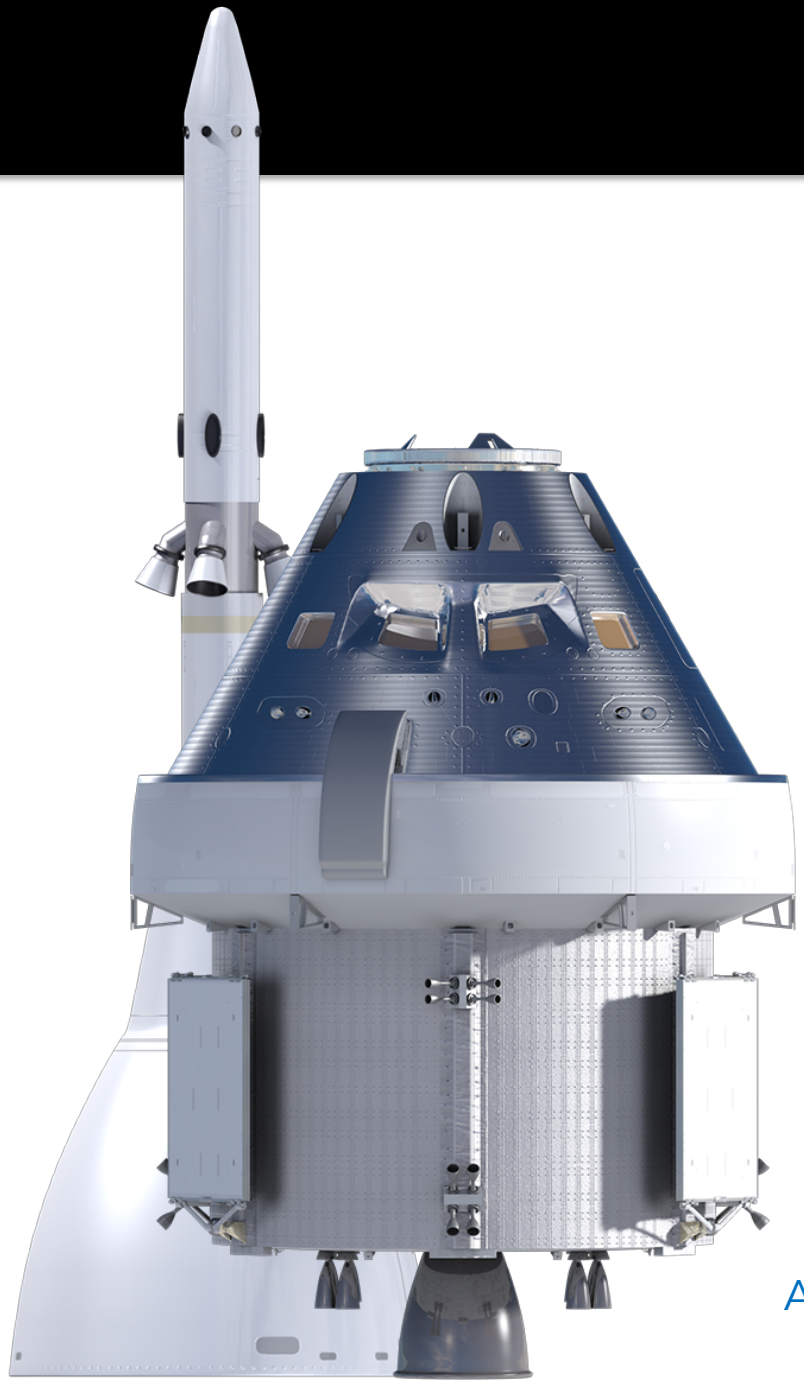
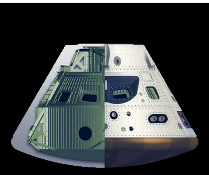


Orion Aerosciences: Aerothermal Database Development

Ryan McDaniel, Orion Aerothermal lead at NASA ARC

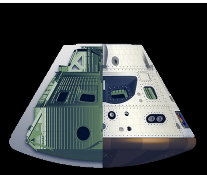
Advanced Modeling & Simulation (AMS) Seminar Series
NASA Ames Research Center, April 7th, 2022

Outline



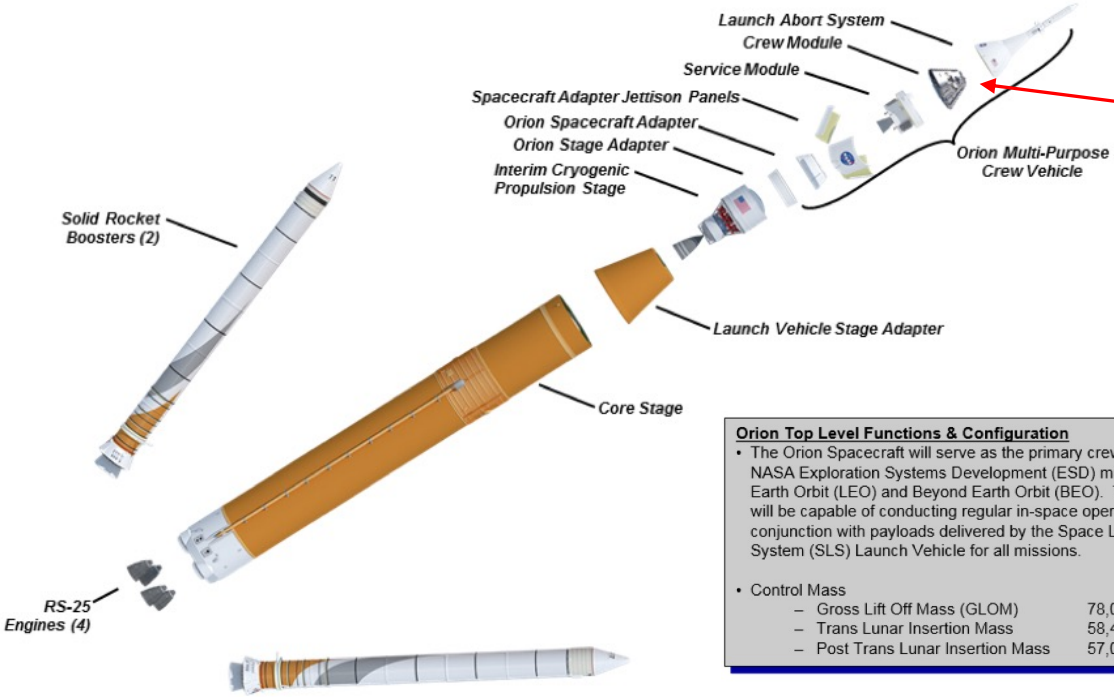
- **Artemis program and hardware description**
- **Schedule of launches**
- **Aerosciences**
  - Relevant Physics
  - Database Development Approach
  - Ground Testing Overview
  - CFD Overview
  - Database construction
- **Smooth body database**
  - Grid generation
  - *DPLR* modeling
  - Solution methodology
  - Solution quality checks
  - Database quality checks
  - Database example
  - Lessons learned

What is Artemis?



- **Artemis will send (up to 4) humans beyond LEO and into deep space. Current focus is sending crew to lunar surface**
  - Partially re-usable spacecraft
- **Artemis Program is managed by NASA, but it is designed and built by a conglomerate of organizations**
  - NASA: Program management, design, hardware provider, operate
  - Lockheed Martin: Design, build/assemble, subcontracting
  - ESA and Airbus: Design, build/assemble for Service Module
- **Unlike partners (SpaceX and Boeing) in Commercial Crew Program, Lockheed Martin builds and sells spacecraft to NASA, and NASA operates spacecraft and manages mission**
- **Orion is part of Artemis Program with EGS, SLS, Gateway, HLS, and Spacesuits**

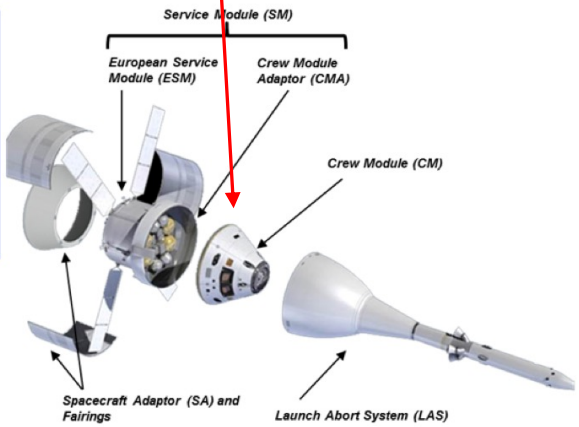
Artemis Modules and Launch Vehicle Stack



Orion Crew Module

Orion Top Level Functions & Configuration

- The Orion Spacecraft will serve as the primary crew vehicle for NASA Exploration Systems Development (ESD) missions in Low Earth Orbit (LEO) and Beyond Earth Orbit (BEO). The vehicle will be capable of conducting regular in-space operations in conjunction with payloads delivered by the Space Launch System (SLS) Launch Vehicle for all missions.
- Control Mass
  - Gross Lift Off Mass (GLOM) 78,010 lbm
  - Trans Lunar Insertion Mass 58,467 lbm
  - Post Trans Lunar Insertion Mass 57,035 lbm



Crew Module (CM) Functions

The CM provides a habitable pressurized volume to support crewmembers and cargo during all elements of a given mission - from Launch Operations to Earth Entry, Descent, Landing, and Recovery.

Spacecraft Adapter (SA) Functions

- Provide structural connection to the launch vehicle from ground operations through orbital injection
- Provide protection for SM components from atmospheric loads and heating during first stage flight

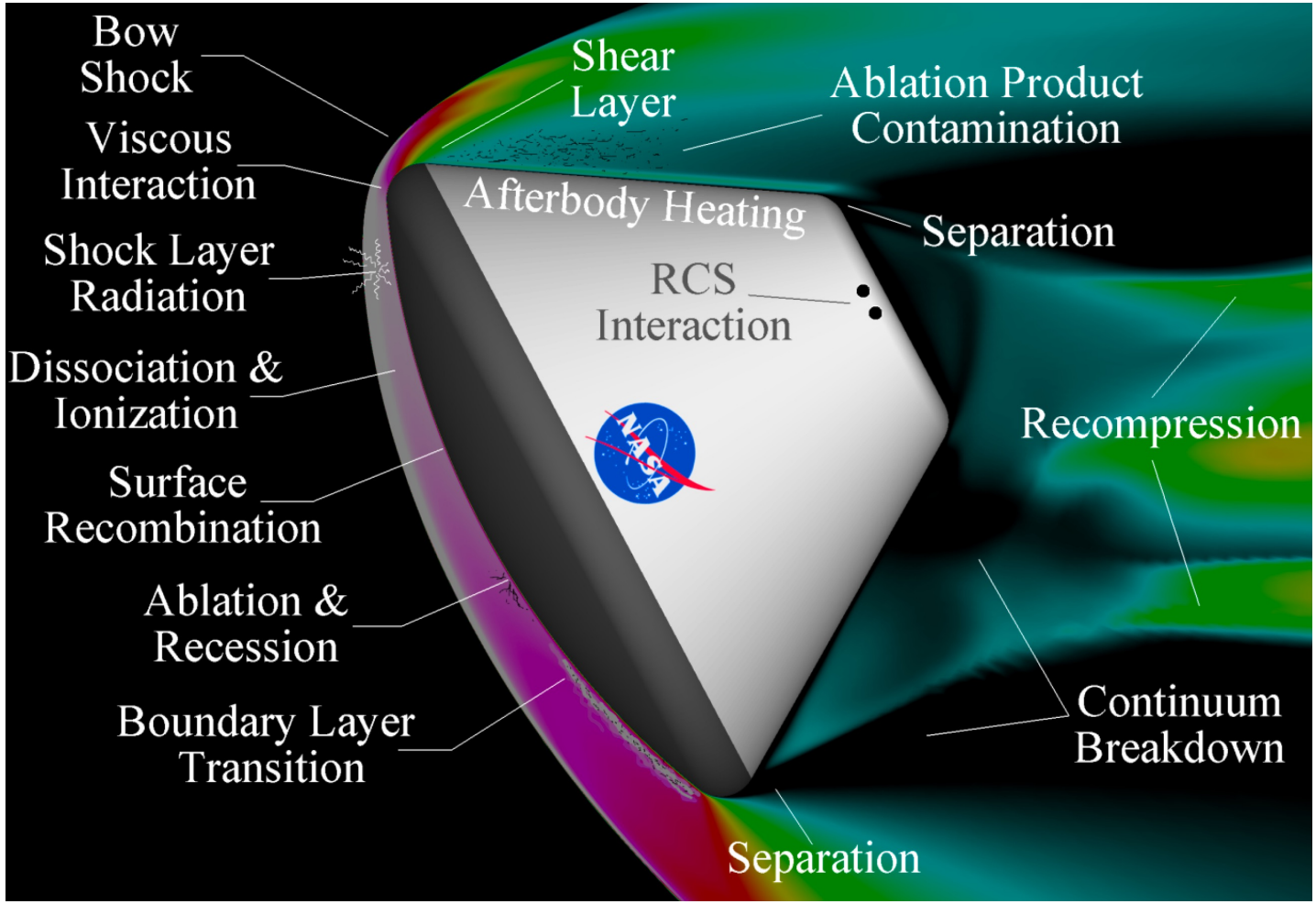
Launch Abort System (LAS) Functions

The LAS provides an abort capability to safely transport the CM away from the launch vehicle stack in the event of an emergency on the launch pad or during ascent.

Service Module (SM) Functions

The SM, comprised of the two subcomponents the Crew Module Adapter (CMA) and the European Service Module (ESM), provides services to the CM in the form of propulsion, consumables storage, heat rejection and power generation.

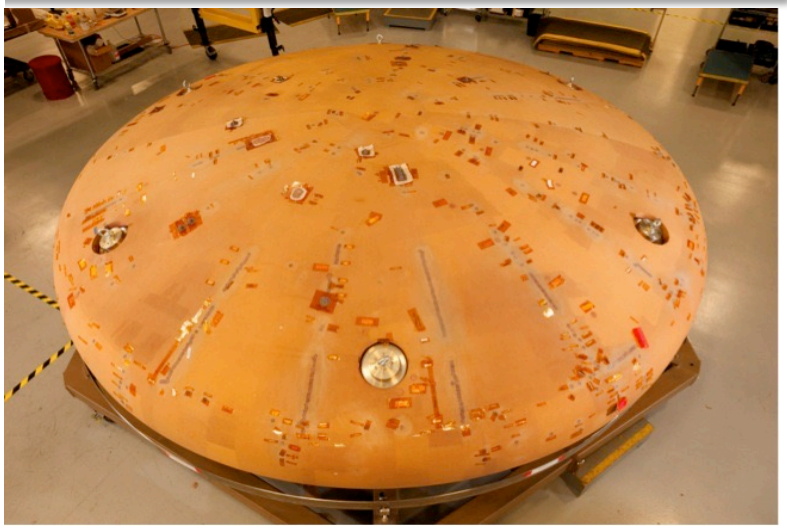
Entry Physics or "Why we need TPS"



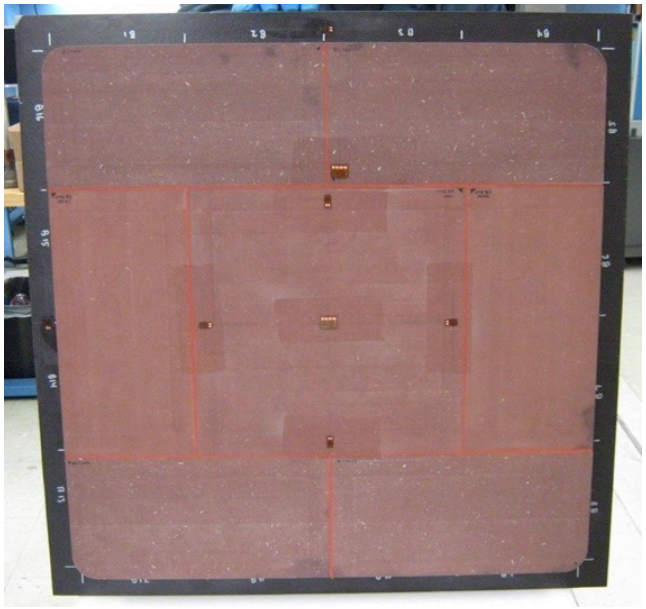
- Lunar entry environments subject Orion capsule to many sources of heating (convective, radiative, catalytic, turbulent transition)
- Thermal protection system (TPS) required to maintain permissible structural temperatures

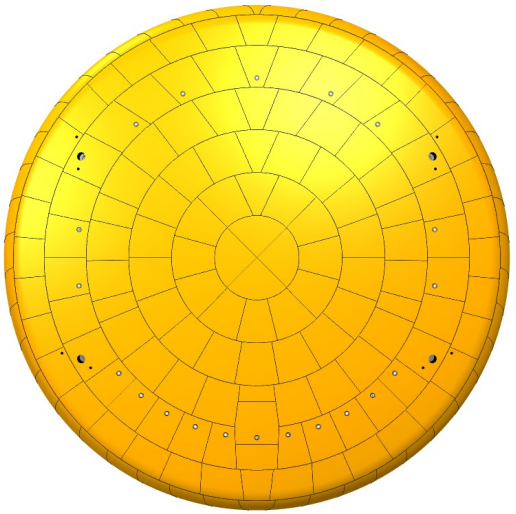
Orion TPS Description - Heat Shield

- **The Apollo Honeycomb/Gunned (HC/G) system was flown on EFT-1 in 2014**
  - Avcoat 5026-39 HC/G
  - Composite/Ti carrier structure



- **For Artemis missions, the Orion baseline is Molded Avcoat blocks**
  - Avcoat 5026-39 M
    - No honeycomb
    - Bonded to the carrier with EA9394 epoxy
  - RTV-560 between blocks
  - Composite/Ti carrier structure
    - Reduced mass from EFT-1

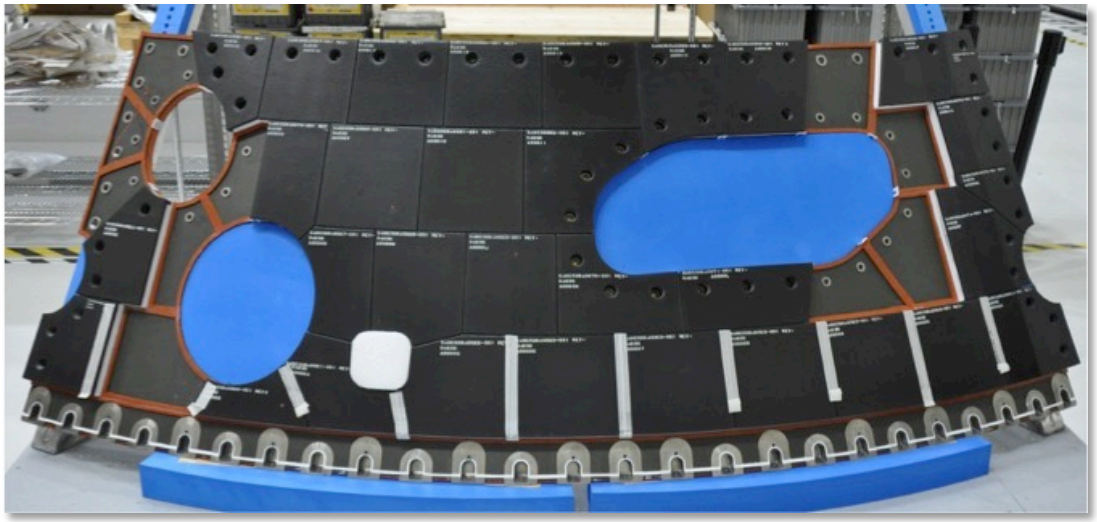




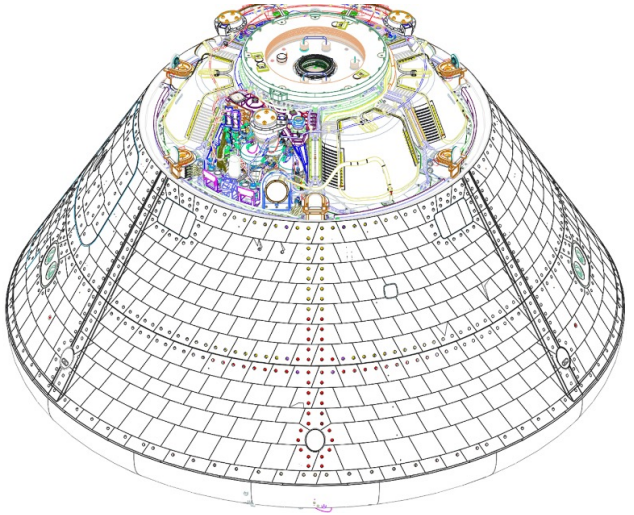
Orion TPS Description – Backshell & FBC

- **Alumina-Enhanced Thermal Barrier (AETB-8 tiles) with RCG over TUFI coating (Shuttle heritage)**
- **Removable panels with threaded tile plugs providing fastener access**
- **Flexible Reusable Surface Insulation (FRSI) used on upper apex surface**
- **Penetrations utilized thermal barriers, carbon phenolic, RTV and FRSI**

Forward Bay Cover, with Side Panel Removed

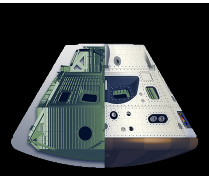


Panel A, Tiles Partially Installed



Back Shell TPS, Wind Side
(Forward Bay Cover Not Shown)

Schedule of Launches



1. **Pad Abort 1 (PA-1): May 2010, LAS test of abort initiation at pre-launch (pad) conditions. Included parachute deployment sequence**

2. **Exploration Flight Test 1 (EFT-1): December 2014, high-speed entry test of EDL systems**

3. **Ascent Abort 2 (AA-2): July 2019, LAS test at maximum dynamic pressure conditions. Did not include parachute deployment sequence.**

4. **Artemis I: June 8, 2022, un-crewed ~1 month mission to lunar distant retrograde orbit (DRO)**

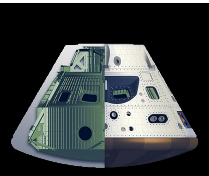
5. **Artemis II: Late 2023, First crewed mission. Lunar fly-by. Rendezvous and proximity operations (RPO) demonstration with SLS upper stage**

6. **Artemis III: Late 2024, Mission objectives TBD, but likely that we'll dock with a target in lunar orbit**

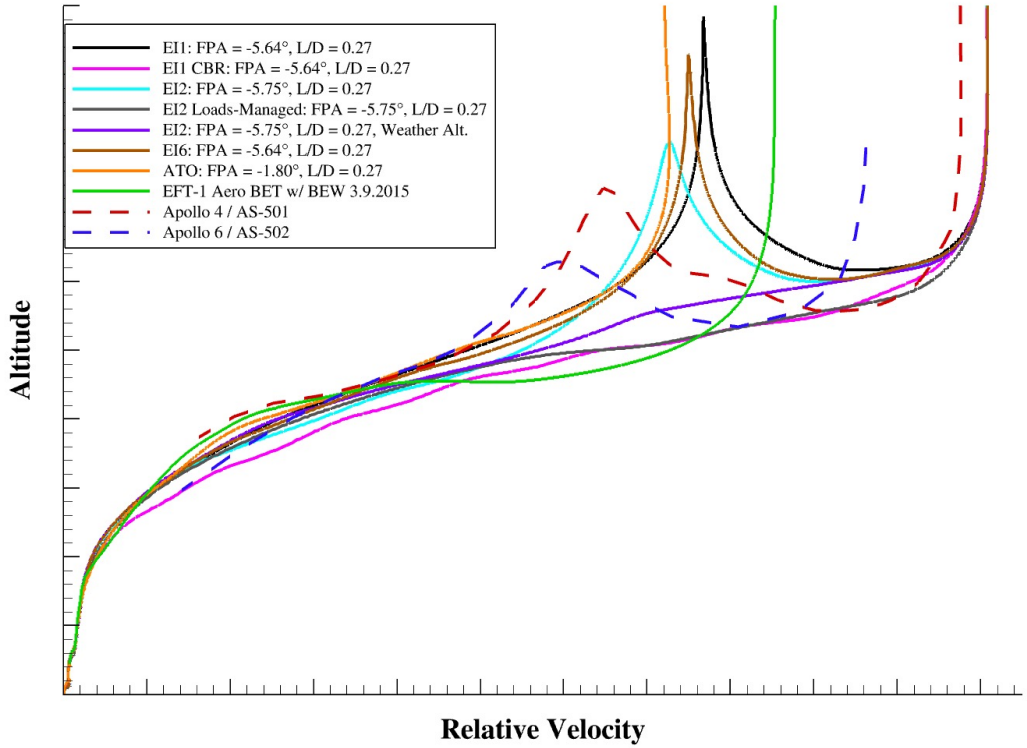
7. **Artemis IV: 2026, Lunar landing. First flight with SLS Block 1B**

8. **Beyond….expecting one flight per year**

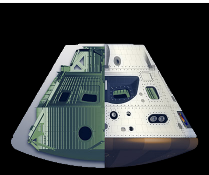
Trajectory Description



- **Critical trajectory parameters for TPS design**
  - Velocity, flight path angle, L/D, and mass → Dictate max. heat flux → Dictates material selection
  - Downrange and time under parachutes → Dictates heat load and thermal soakback → Dictates material thickness
- **Lunar return environments are much more extreme than LEO return**
  - Convective heating scales with V^3 and radiation heating scales with V^{8+}
  - Mars return is even more challenging at 14 km/sec!
- **Orion designed to enter faster than and fly further than Apollo**

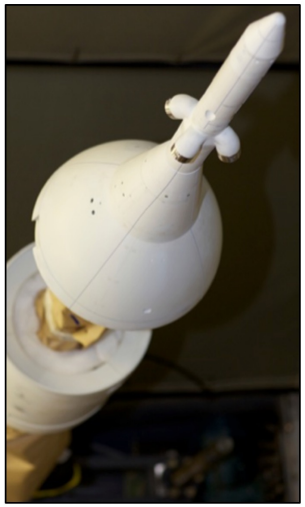


Database Development Approach

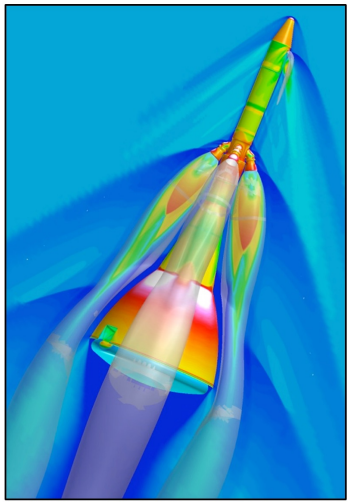


- **Orion Aerosciences is responsible for providing the aerodynamic (for trajectory design and controls) and aerothermal databases (for TPS design, thermo-structural analyses)**
- **Aerothermal database products: smooth body ATDB, set of feature augmentation models, margin policy, radio blackout database**
- **Developed by leveraging various data sources and levels of fidelity**
  - Historical flight data (mainly Apollo and Orbiter)
  - Historical ground test data
  - Engineering methods
  - Orion-specific ground test
  - Orion flight testing
    - PA-1, EFT-1, AA-2, EM-1
  - High-fidelity computational methods
    - *DPLR, LAURA, Loci-CHEM, OVERFLOW, DAC, HARA, NEQAIR, FUN3D, US3D, CHAR, Cart3D, CBAERO*
- **Products are typically built on multiple data sources (i.e. 2 ground tests OR 1 ground test and CFD) to help validate approach and develop design margins and prediction uncertainties**

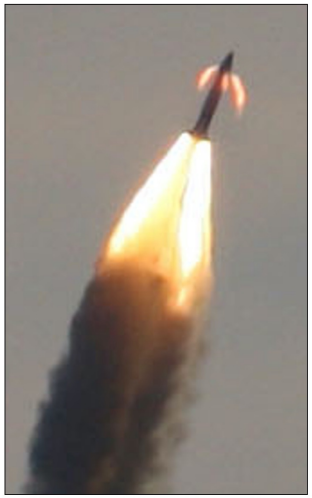
Data Source	Pros	Cons
Ground Test	Some real physics	$$, small scale, not all physics, long lead
Mod. & Sim.	All physics at full scale, $, quick	modeling errors
Flight Test	All physics at full scale	$$$, infrequent, sparse data, challenge to interpret



Ground Testing

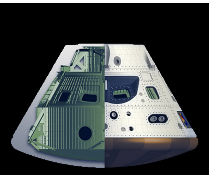


Modeling and Simulation



Flight Testing

Aerosciences Testing for Critical Phases



Test Campaign Color Key
Orion Aerothermal Ground Test
Orion Aerodynamic Ground Test
Orion Flight Test
Other Orion Test
Non-Orion Data Source

Radiative heating: 33-, 34-, 43-, 44-, 71-, 72-, 96-, & 97-CH, Apollo, FIRE II, EFT-1
Convective heating: 31-, 35-, 36-, 40-, 56-, 67-, 91-, 113-, & 124-CH, Apollo, EFT-1
Hypersonic aero: Apollo

CM-SM R&R heating: 30-, 64-, 66a-, 86-, 87-, 102-, 126-, & 127-CH, EFT-1
Boundary layer transition: 35-, 36-, 40-, 56-, 67-, 127-, 128-, 131-, & 132-CH, Apollo, EFT-1
Ablator interactions: EFT-1, 39-, 41-, 69-, 127-, 128-, 131-, & 132-CH, Arcjet, SpaceX Dragon, Apollo, 89-CA, 133-CA
RCS interactions: 37-, 63-, 66b-, 95-, & 123-CH, EFT-1, Apollo
Cavity & protuberance heating: 66b-, 95-, & 123-CH, EFT-1

Re-Entry

On Orbit

Exo-atmospheric aero, aerothermal, and plumes: Space Shuttle Orbiter, ISS

Hypersonic Abort

Transonic & Supersonic Abort

LAS Abort Boost
Aero: 26-, 83-, 60-, & 75-AA, PA-1, AA-2
Heating: PA-1, AA-2, PITP (SLS), ST-1

Super and Transonic Aero
Static: 3-, 5-, & 9-CA, EFT-1
Dynamic: Apollo, EFT-1

Subsonic Aero
Static: 89-, & 133-CA, EFT-1
Dynamic: 18-CD, 27-AD, EFT-1

LAS Abort Coast
Aero: 75-, & 76-AA
Heating: 103-AH, PA-1, AA-2, EFT-1, AM-QM-1

FBC jettison: 122-PA, 125-CD, Apollo

Parachute aero (2-main): CPAS Drop Tests 3-2, 3-8, 3-11, 3-12

Pad Abort

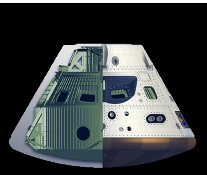
LAS Abort Reorientation
Aero: 27-AD
Heating: PA-1, AA-2

LAS Abort Separation
Aero: 24-. 25-, & 61-AA
Heating: PA-1, AA-2, EFT-1, JM-QM-2

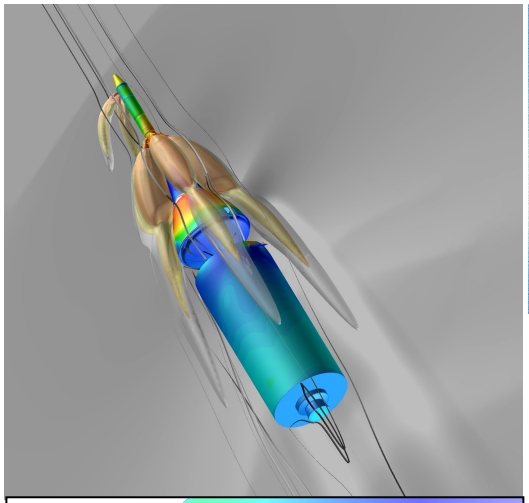
High risk environments utilize flight testing and ground testing from multiple facilities
- Aero example: Transonic LAS abort
- Aerothermal example: Boundary layer transition

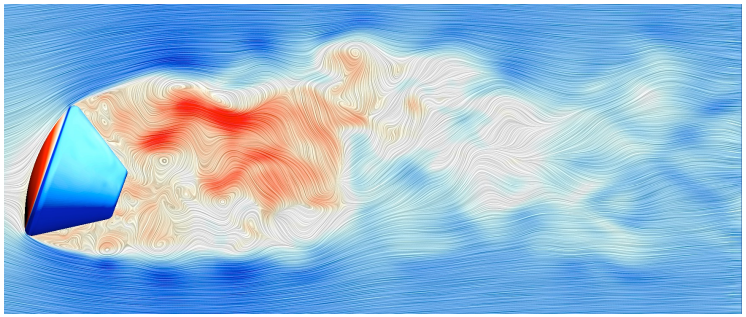
All phases utilize high-fidelity computational modeling
- 10's of thousands of simulations used for database development
- Validation rooted in ground tests, flight tests, and historical data

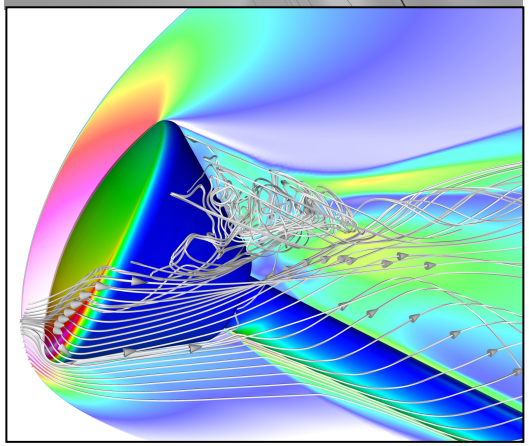
CFD Overview

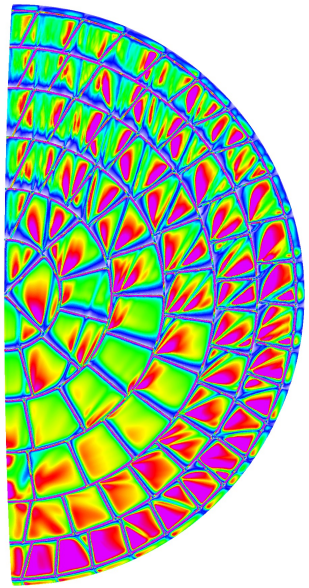


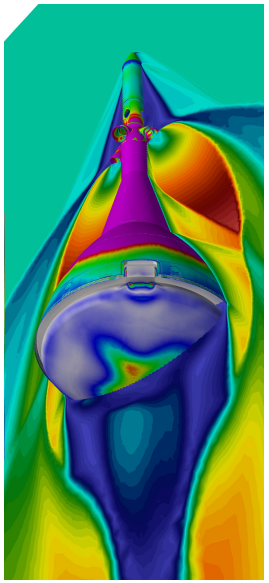
- **CFD is used to develop environments for Aerodynamics and Aerothermodynamics for all phases of flight**
- **We attempt to validate CFD tools utilizing ground and flight test data before applying it in design analyses**
- **Key challenges for CFD in Orion Aerosciences**
  - Aero: Complex geometries, turbulence, wake flows, plume flows, fluid-structure interaction (parachutes)
  - Aerothermal: Complex geometries, turbulence, wake flows, plume flows, gas-surface chemical interaction, radiation

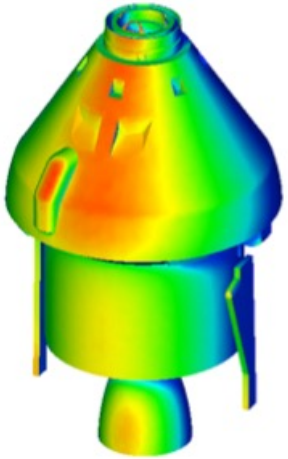


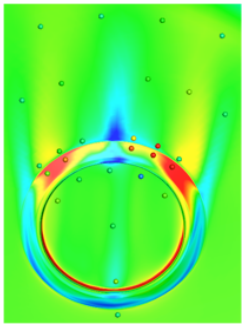


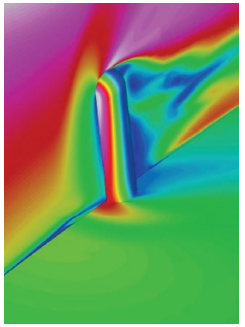




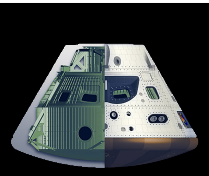




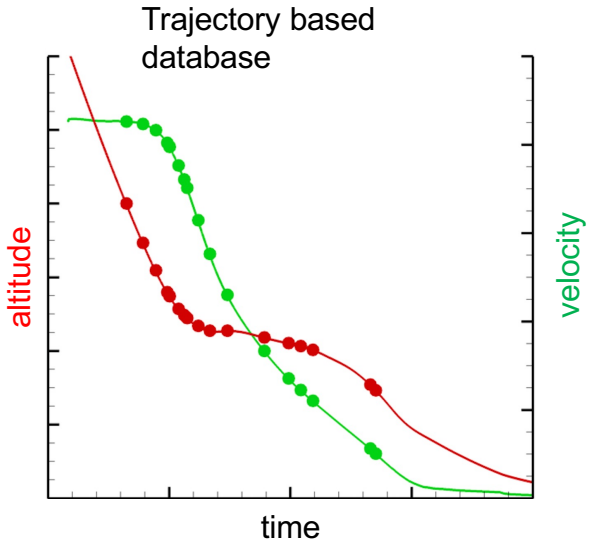


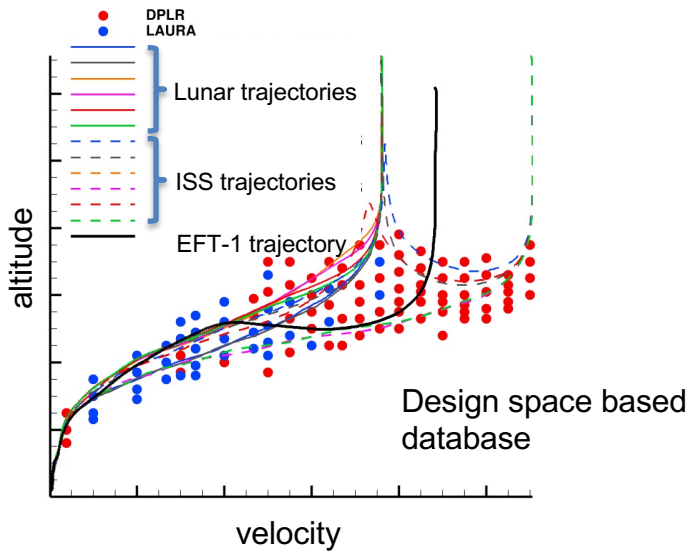


Database Construction

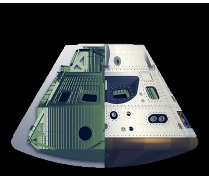


- **Database construction methodologies**
  - Trajectory based database: Relatively small number of CFD solutions computed along trajectory. Body points selected for TPS sizing. Heating along trajectory computed by curve fitting CFD predictions at body points with form $q_w = C\,\rho^m\,V^n$
    - Historically used for robotic missions with single, well defined entry trajectory
  - Design space based database: Relatively large of solutions computed that span range of trajectories in 3-D flight space (Mach - dynamic pressure - angle of attack). Heating at any surface point at any point in time computed by interpolation
    - Human rated missions require increased operational flexibility (aborts, multiple flights with different entry scenarios)
    - Robotic missions have started adopting this approach because increased design flexibility

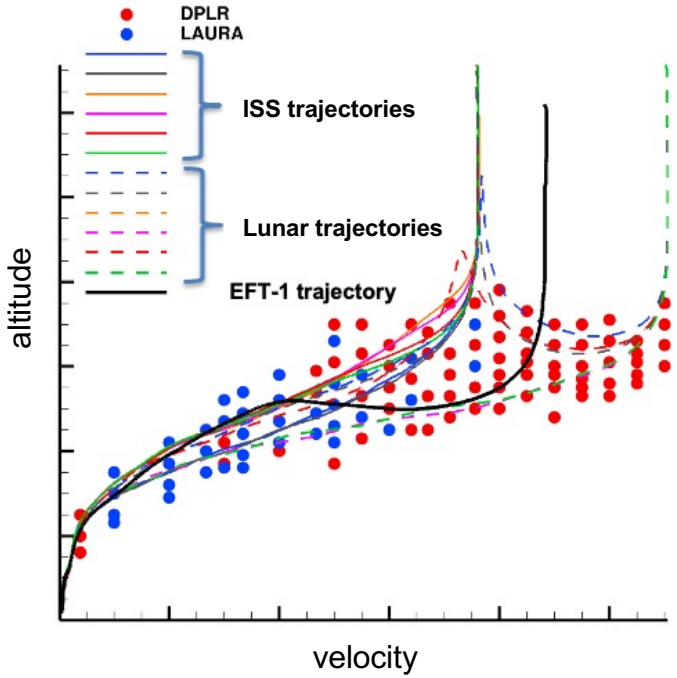




Database Coverage

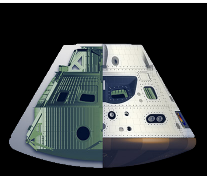


- **Continuum database of 941 CFD solutions (*DPLR* and *LAURA*)**
  - 3 cases for each V-alt pair: laminar fully catalytic, turbulent fully catalytic, laminar fully catalytic heat shield and RCG back shell
  - 3-5 angles of attack for each case

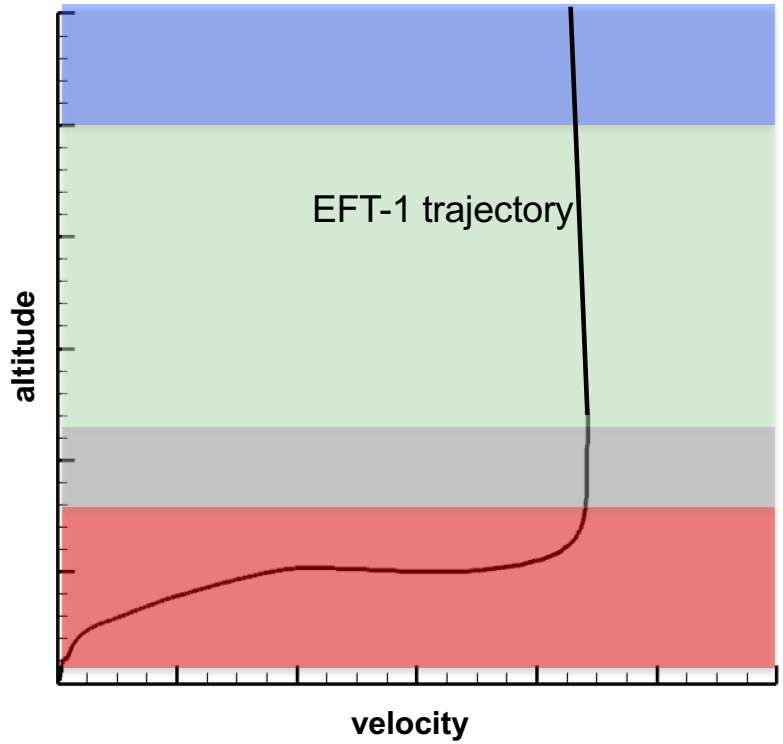


- **Noncontinuum database of 493 *DAC* solutions**
- **299 coupled *LAURA-HARA* radiation cases**

High Altitude



- **Continuum CFD database begins at 75 km (Kn_D = 3.78E-4)**
- ***DAC* database of 393 solutions extends from 250 km (Kn_D = 111.0) to 105 km (Kn_D = 0.06)**
- **In between, database populated with engineering-level heating predictions from *CBAERO* corrected with factor based on *DAC* solutions**



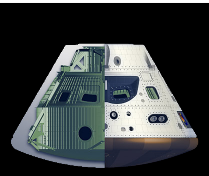
engineering free molecular solutions

DAC solutions

CBAERO corrected with *DAC*

CFD

Outline



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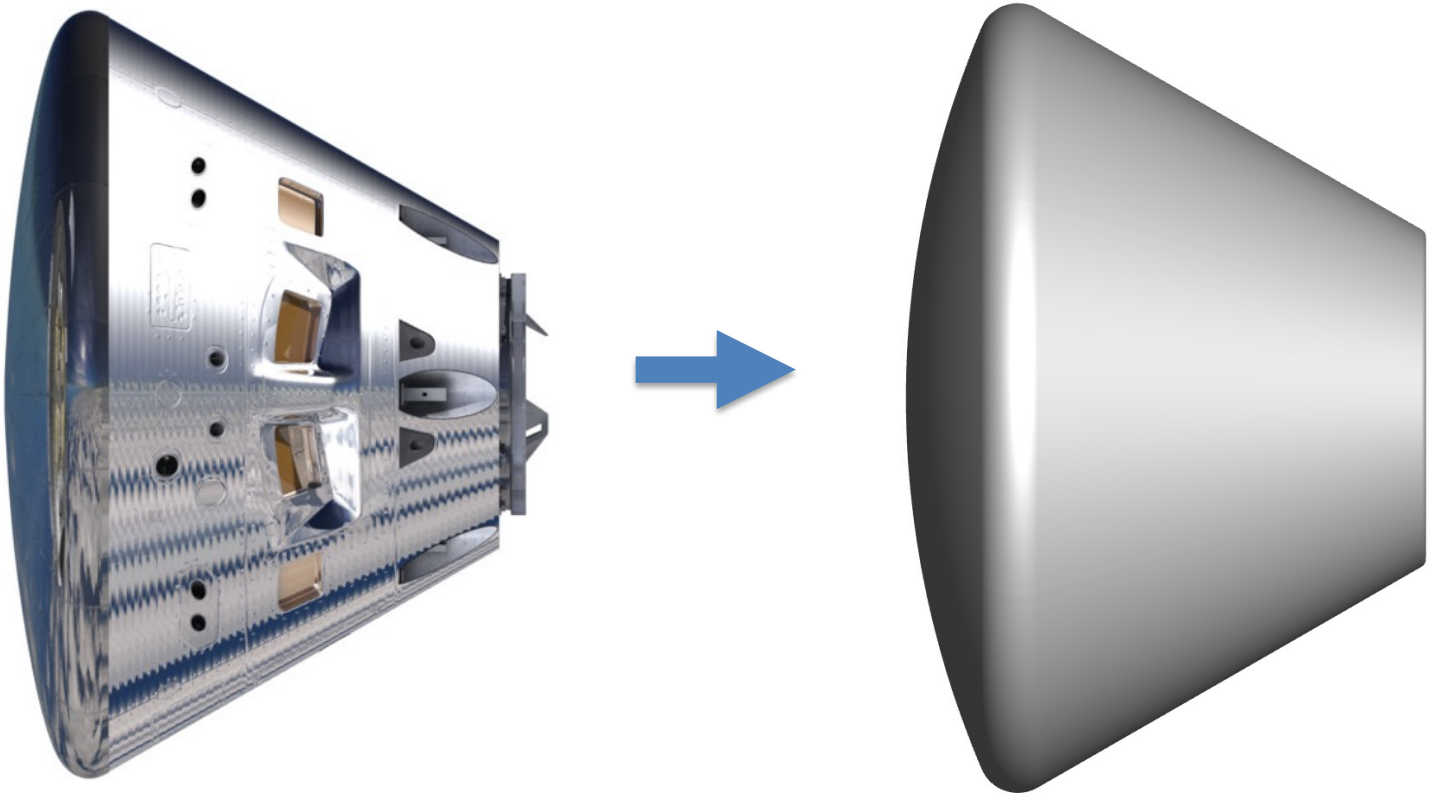
  - Database Development Approach
  - Ground Testing Overview
  - CFD Overview
  - Database construction
- **Smooth body database**
  - Grid generation
  - *DPLR* modeling
  - Solution methodology
  - Solution quality checks
  - Database quality checks
  - Database example
  - Lessons learned

Geometry Simplification

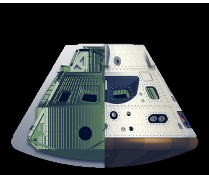
Flight geometry

CFD geometry



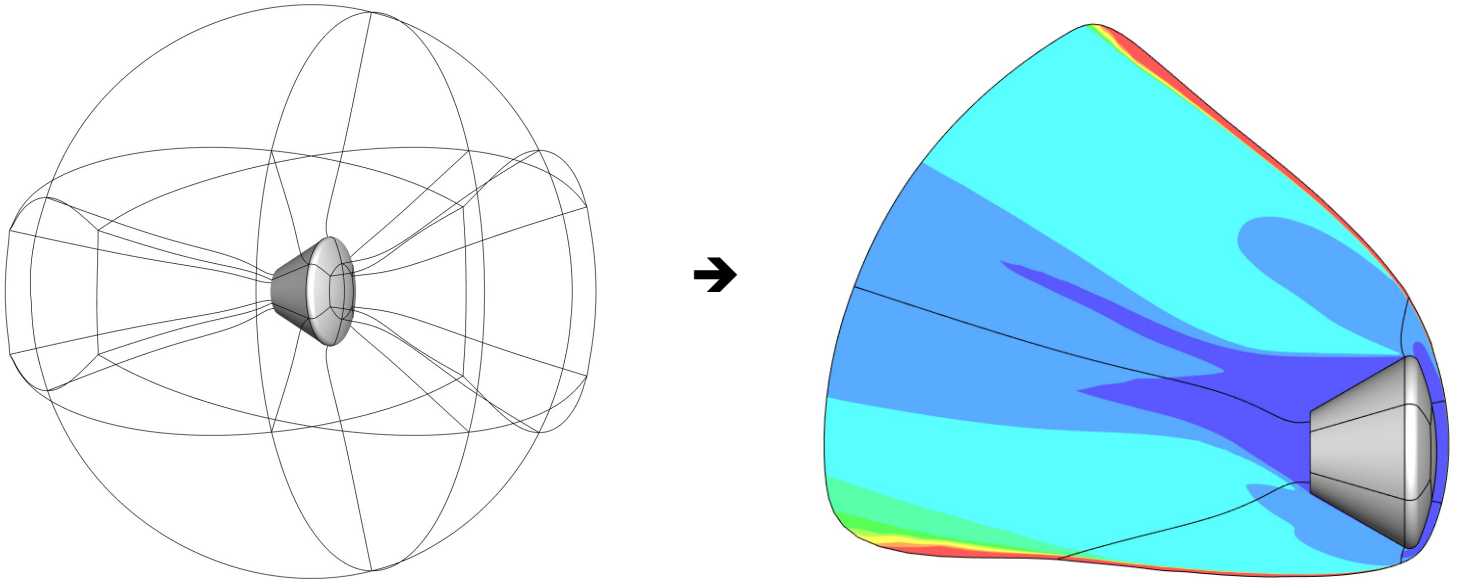
- Geometric features (RCS, cavities, protrusions) handled with 46 individual heating augmentation models
  - $q_{w,feature} = AF \times q_{w,SOML}$

CFD Methodology: Grids

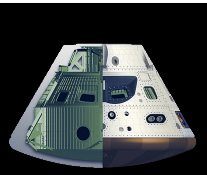


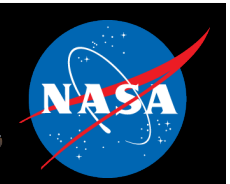
- **Common volume grid for *DPLR* and *LAURA* containing 16.4 million points with 102,000 surface points and 161 points in the off-body direction**
- **Initial outer boundary large enough to contain bow shock for all possible flight conditions**
- **Grid tailoring routines within flow solvers aligns outer boundary with bow shock and adapts wall spacing to maintain cell Reynolds of unity**

$$\mathrm{Re}_{cell} = \frac{\rho_w a_w \mu_w}{\Delta n}$$

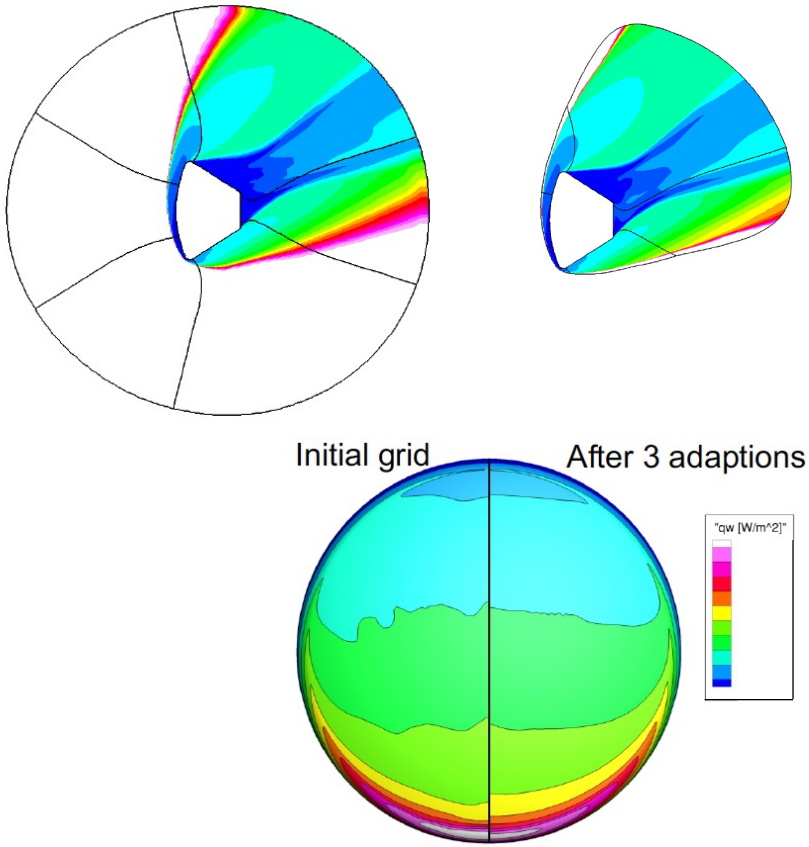


Why Adapt?

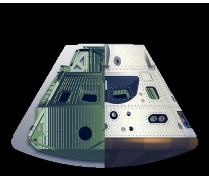




- **Shock-capturing CFD codes can generate numerical errors across strong shock if grid is not carefully aligned with the shock**
- **Errors propagate from shock to vehicle surface, where they show up as non-physical heating distributions**

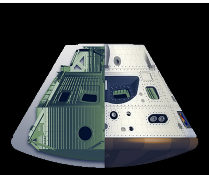


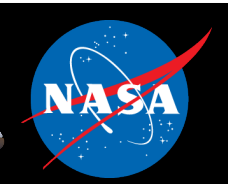
DPLR Modeling



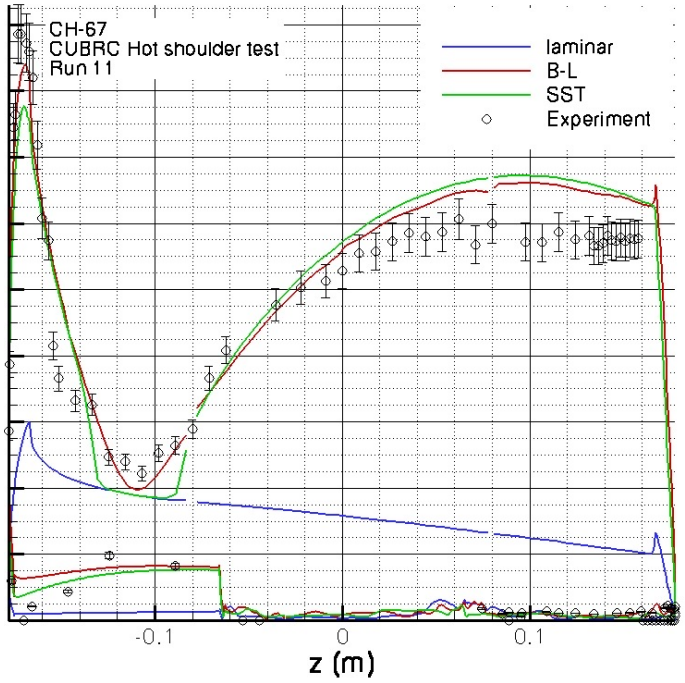
- **Standard set of *DPLR* ver. 4.02 input files available to all users**
- **Inviscid fluxes computed with modified 3rd order Steger-Warming flux splitting**
- **Viscous fluxes computed with 2nd order central differencing**
- **Transport properties computed with Yos mixing rule**
- **Diffusion coefficients computed with SCEBD model**
- **Coupled finite rate chemistry modeled with NASA Lewis curve fits**
- **Two temperature (T-T_v) thermal nonequilibrium**
- **Fully laminar or turbulent (Baldwin-Lomax model although 2-equation SST model also available)**
- **Different air chemistry models for different flow regimes**
  - Low enthalpy wind tunnel freestream conditions (M_∞<6) use perfect gas
  - Low velocity freestream conditions (U_∞<8 km/s) use 5-species air
  - High velocity freestream conditions (U_∞>8 km/s) use 11-species air

Turbulence Model Selection

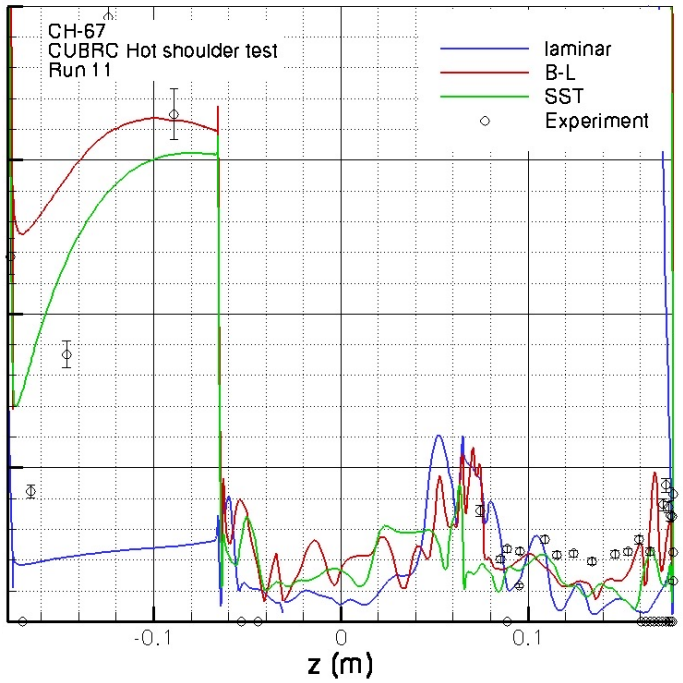




- Ground tests used to validate turbulence models
- Test in CUBRC LENS-1 shock tunnel showed simple algebraic Baldwin-Lomax model performs as well as 2-equation Shear Stress Transport model in separated region and does not have numerical transition issue in attached flow

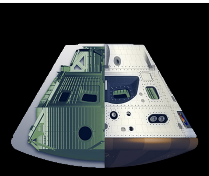


forebody centerline

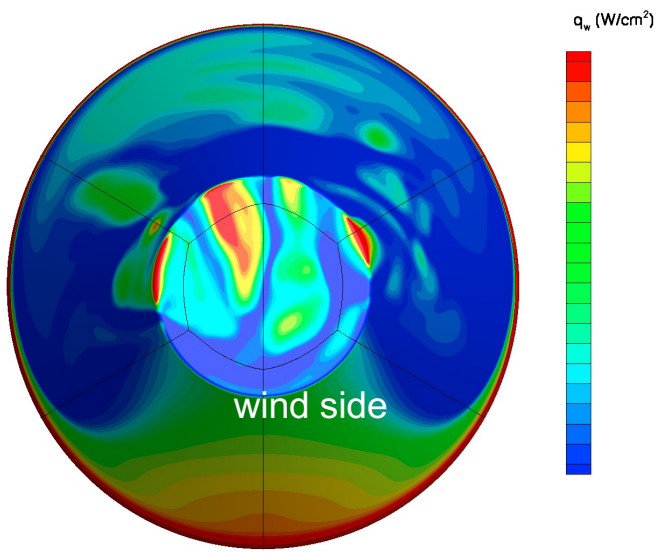


aftbody centerline

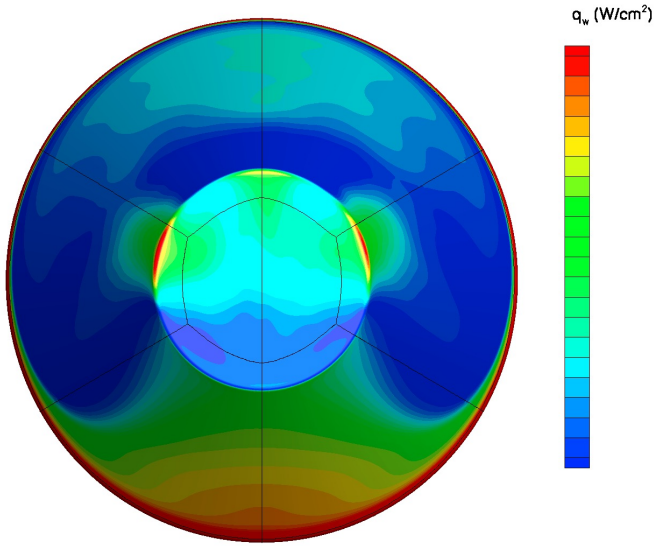
CFD Methodology: Time Averaging



- **Chaotically moving vortices in separated region produce time-varying heating pattern**
- **Regions of high and low heating not representative of heating values seen during flight**
- **CFD solutions are time averaged to produce more representative heating values**
- **Full body solutions needed to allow degree of freedom across symmetry plane**

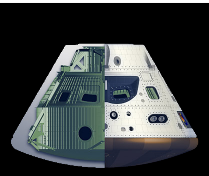


instantaneous solution



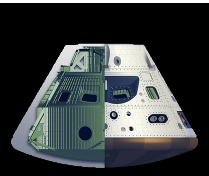
time averaged solution

Script



- **Early in program, individual CFDers had their own best practices which led to inconsistencies in solution quality**
  - Poorly defined convergence. “Run a long time until converged”
  - Poorly adapted grids
  - Typos in input files leading to incorrect modeling or wrong freestream conditions
- **Program spans decades**
  - New people join with varying familiarity with running *DPLR*
  - Experienced users expected to juggle dozens of cases at a time
- **Scripts were developed to automate every step of smooth body solution generation**
  - Input file setup
  - Grid adaption
  - Convergence assessment
  - Solution quality check, “qual check”, and ATDB file generation
  - Archiving solutions

Input File Setup and Grid Adaption



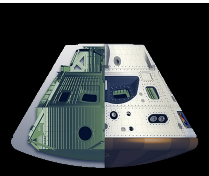
- **setup_chun script copies grid and input files into local directory and sets freestream conditions pulled from *cases.txt* which contains list of CFD cases with freestream conditions defined by 1976 U.S. Standard Atmosphere Model**
- **run_Chun.5sp.pbs**
  1. Initialize half-body "peach pit" grid with freestream and ramp up CFL
  2. 4 cycles of converge-and-adapt on 4-4-1 half-body grid
  3. 4 cycles of converge-and-adapt on 2-2-1 half-body grid
  4. 4 cycles of converge-and-adapt on 1-1-1 half-body grid

  radial_interp
  https://github.com/nasa/cfdtools

  5. Mirror the grid
  6. 4-4-1 full body grid initialized with freestream*
  7. 2-2-1 full body grid
  8. 1-1-1 full body grid

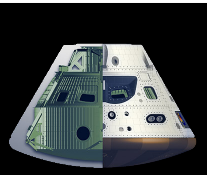
  fconvert
- **run_Chun.11sp.pbs similar, but with additional sequences for robustness**
- **Techniques to speed grid adaption**
  - Performed on half-body grid
  - For 11-species cases, performed on 5-species solutions with single final adaption on 11-species solution
- **Grid mirroring also ensures symmetric grids to reduce possible grid effects**
- **Less than 8 hours on 360 processors**
- **Nearly bullet proof**

Convergence Assessment

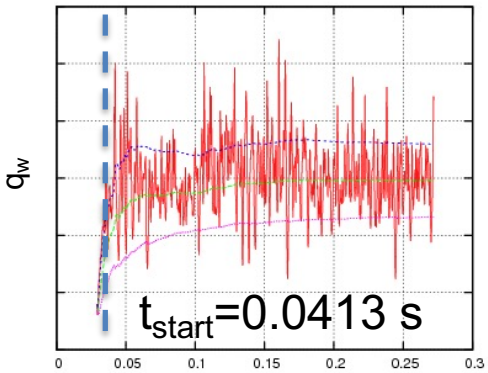


- **run_dplr_stats.pbs**
  1. Runs 20 batches of 2000 iterations at constant CFL with time-averaging
     - save surface averages for each batch (surf_avg_1.plt, surf_avg_2.plt, …)
     - monitor q_w at 8 body points in separated region
  2. Determine when to start averaging
     - End of transient determined by computing moving average at 8 BPs
     - Transient passed when moving average at all 8 BPs converges to within 2%
  3. Determine when to stop averaging
     - When difference between averages over progressively longer time windows is within tolerance of 5%, average has converged
     - If 5% tolerance not reached, additional run time is required
- **60 hours on 360 processors. Less if solution converges before 20 batches**

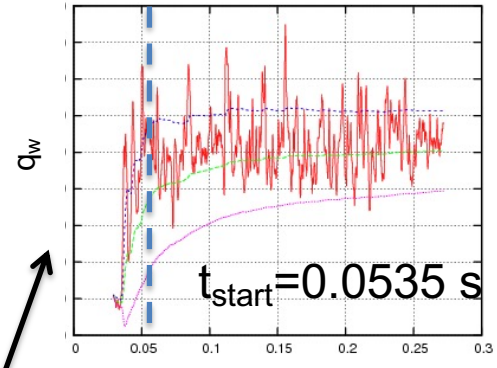
Body Point Histories



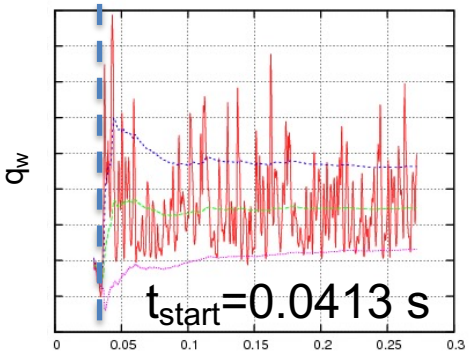
BP1



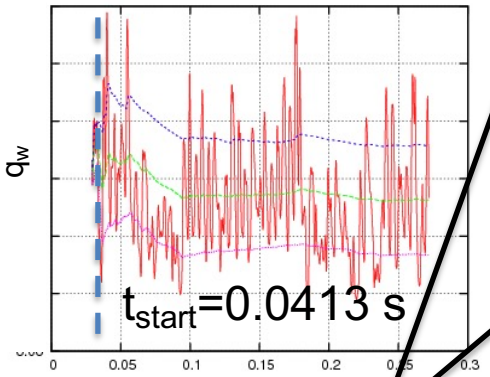
BP2



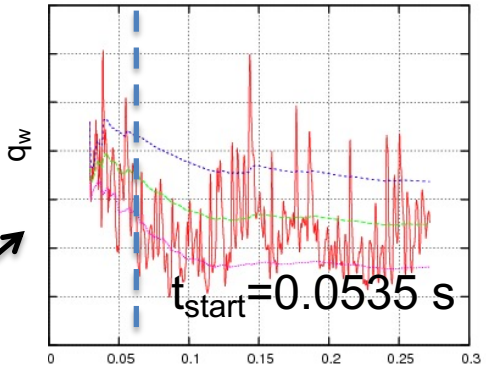
BP3



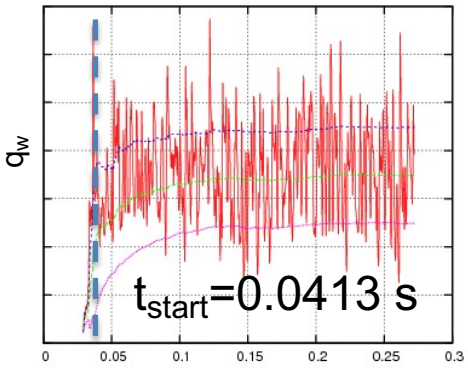
BP4



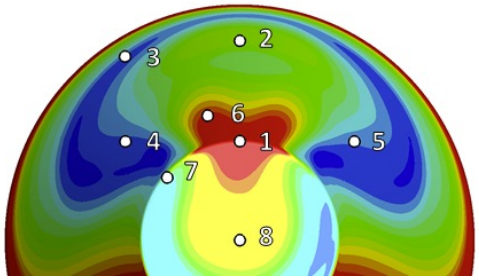
BP5



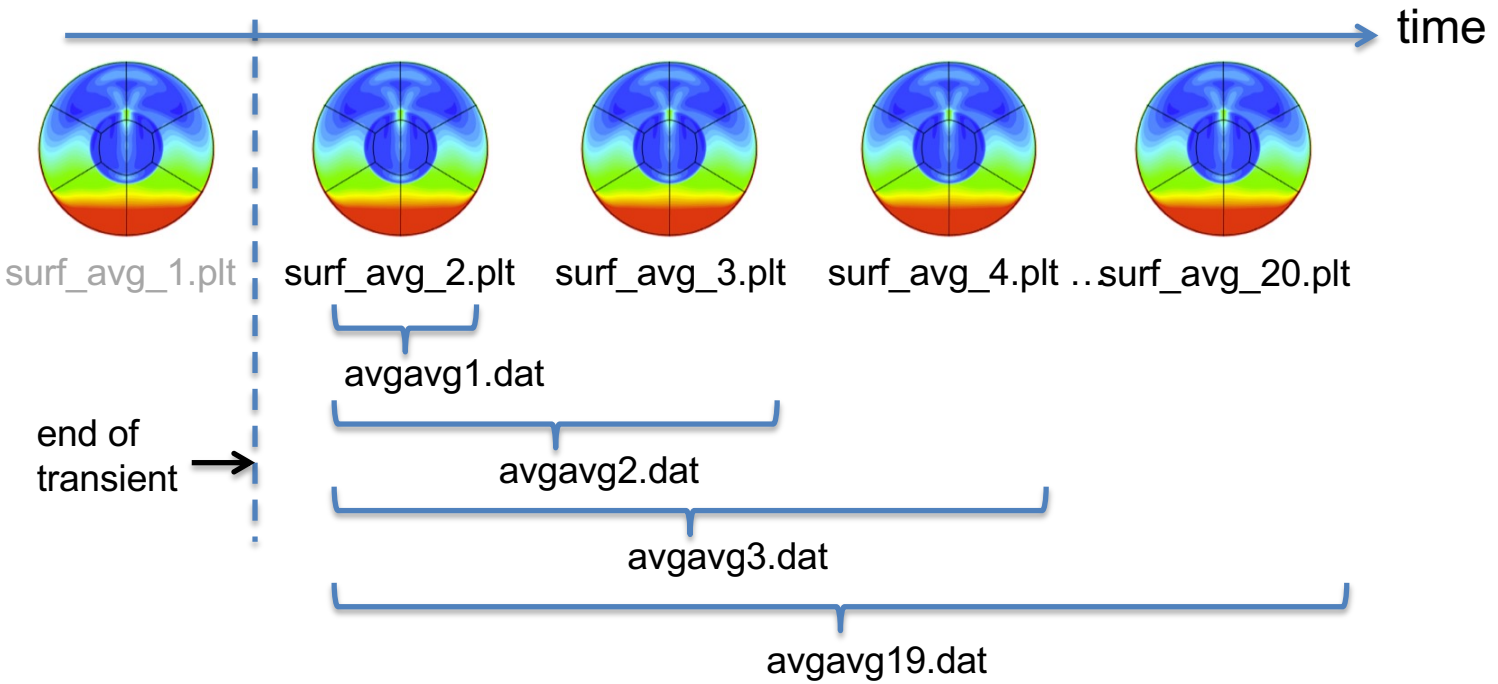
BP6



BP2 and BP5 determine start time for this case

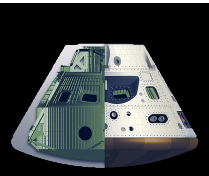


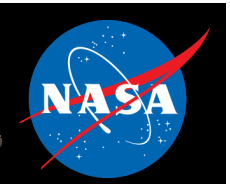
Convergence Criterion (Average of Averages)



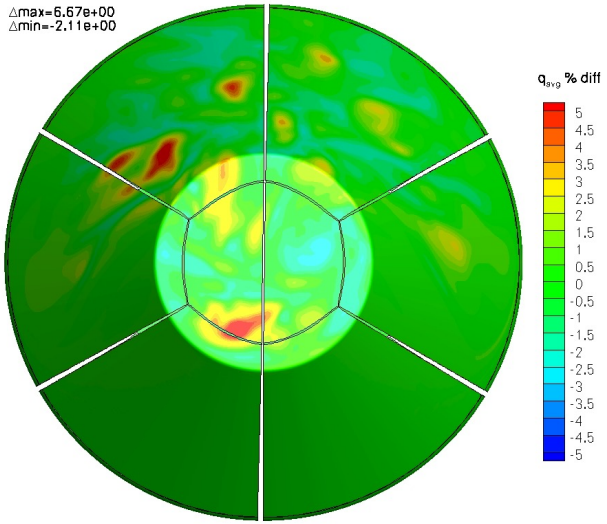
- Convergence reached when at every grid point, $avgavg_n - avgavg_{n-1} < 5\%$

Convergence in Separated Region

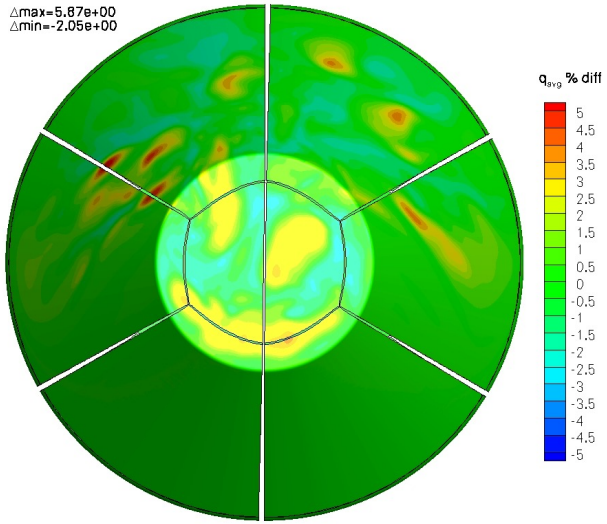




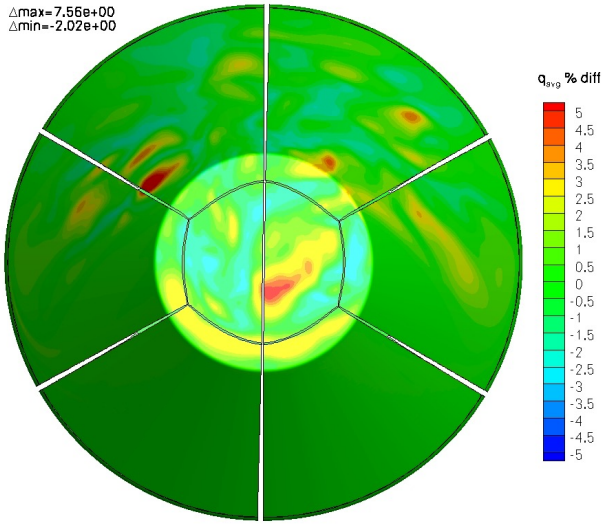
diff 8k and 10k iterations



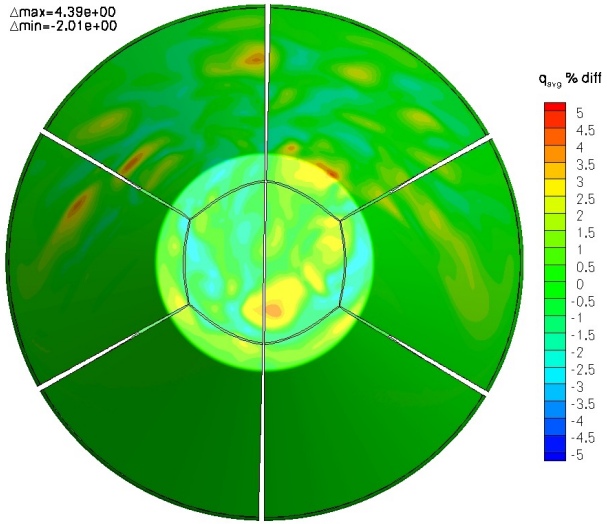
diff 10k and 12k iterations



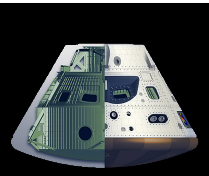
diff 12k and 14k iterations

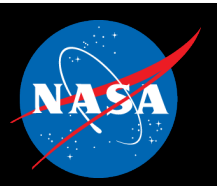


diff 14k and 16k iterations



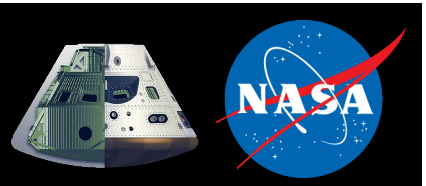
Solution Quality Check



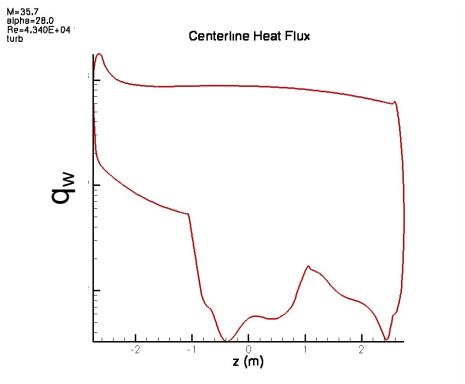


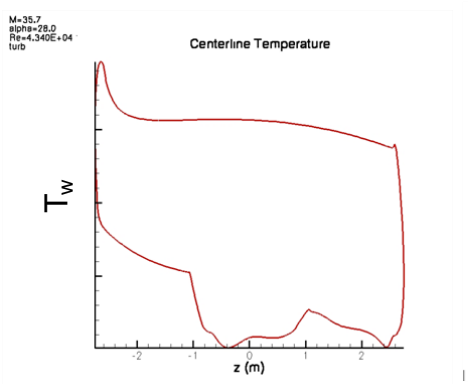
- **Set of scripts, text files, and *Fortran* codes used to postprocess all solutions before release**
- **Process includes**
  - Set of surface contours, pitch plane contours, and centerline plots for final solution
  - Surface contours of difference in surface properties between multiple successive solutions to check for convergence
  - Iteration history of aerodynamic coefficients to check for convergence
  - Log file containing modeling options
  - Aerodatabase template file
  - Aerothermal database file
- **CFD team examines images together in conference room with projector**
  - All must agree to pass or fail
  - If a case does not pass qual check, owner makes adjustments to fix problem (further adaptions, lower CFL, adjust dissipation, etc.)
  - Once passed, case is archived on Pleiades and NAS

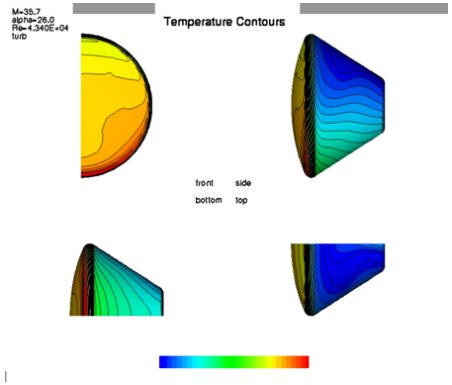
Sample Solution Quality Check Images (Centerline and Contour Plots)

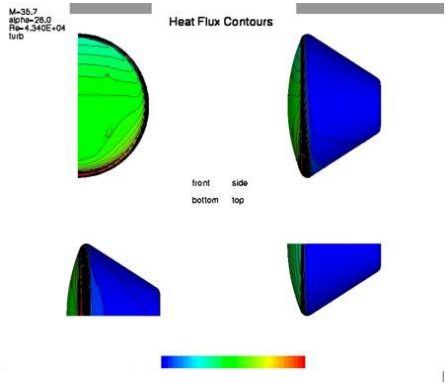


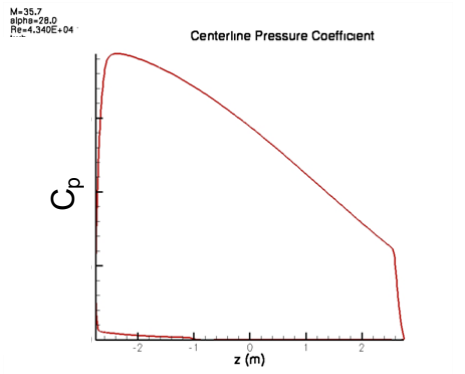
- **User executes "qc.script" which generates qual check images, compares DPLR input file with best practice input file, and flags any discrepancies**

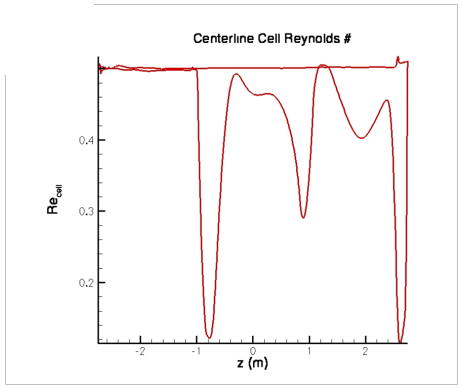


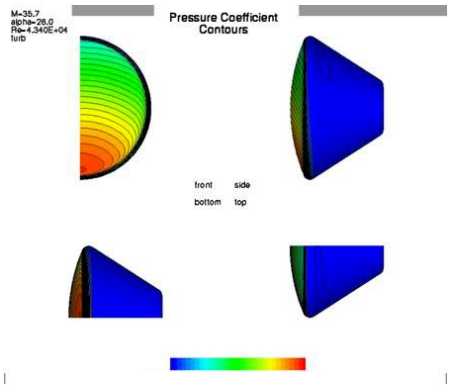


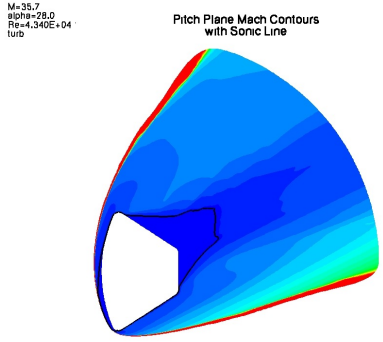




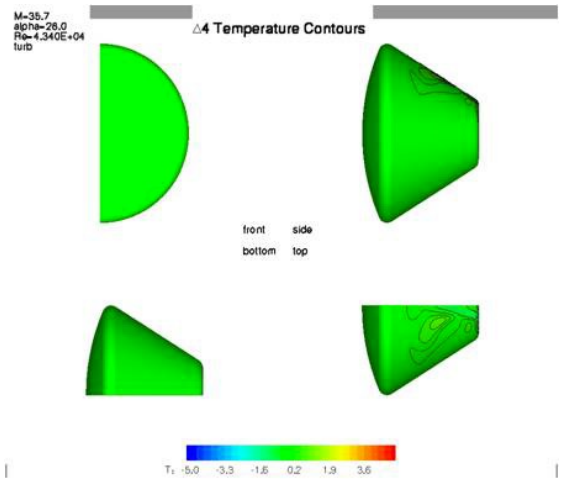


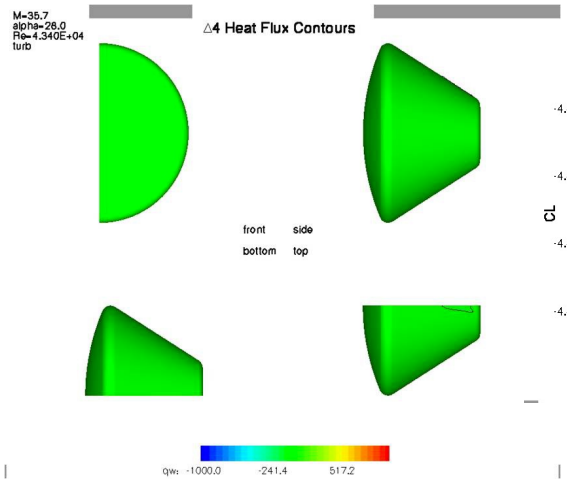


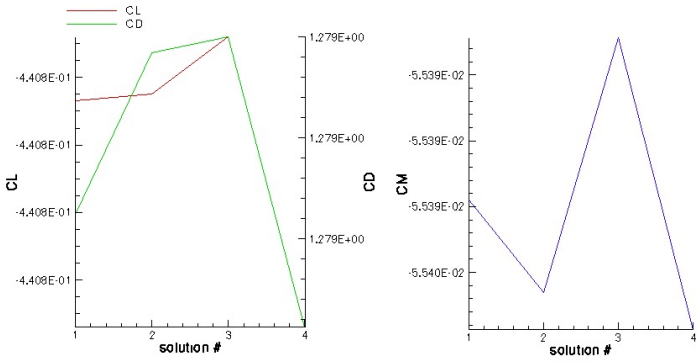


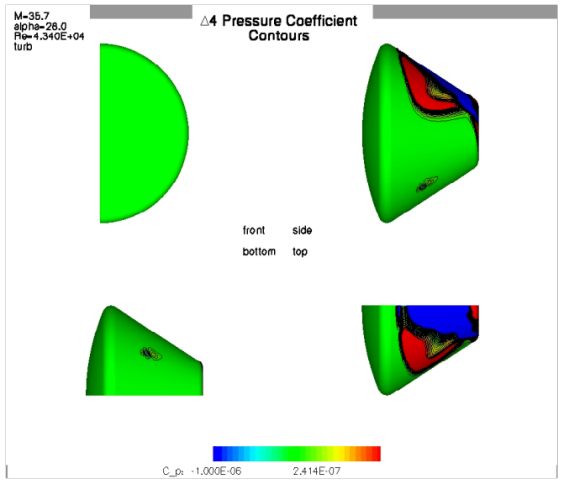


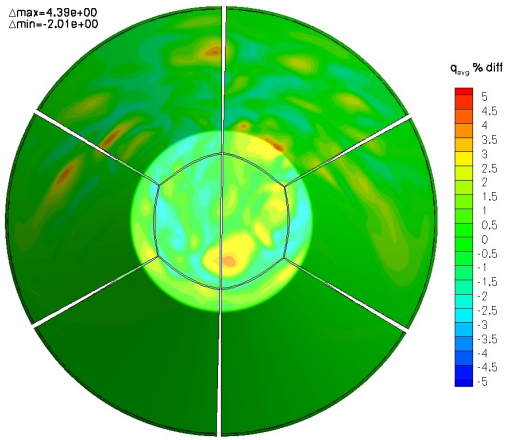
Sample Solution Quality Check Images (Convergence Plots)



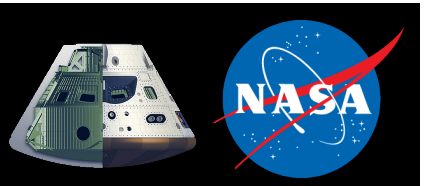




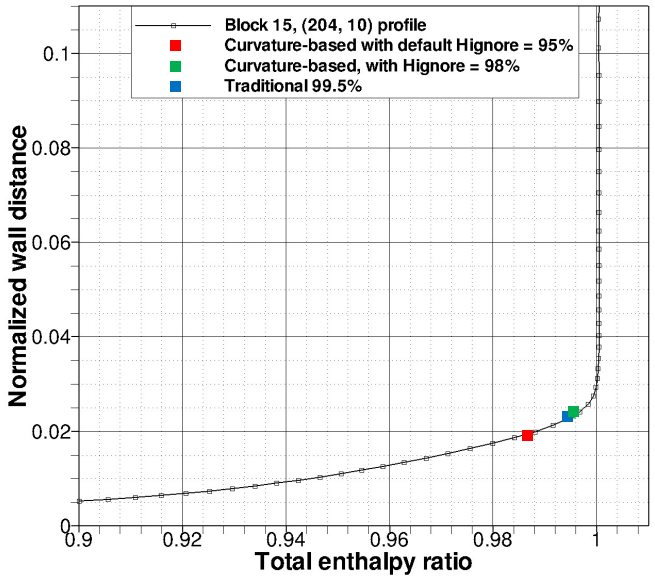




ATDB File



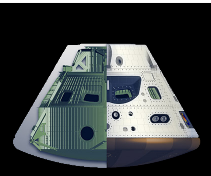
- *Blayer** developed during Shuttle RTF to detect boundary layer edge
  - Traditional method, 99.5% H_∞
  - Curvature method, peak curvature in H ratio profile



- *Blayer* file is *Tecplot* ASCII format file containing wall and edge values: x_w, y_w, z_w, ρ_w, P_w, T_w, $T_{v,w}$, $h_{0,w}$, μ_w, $c_{s,w}$ (species mass fractions), e_w, q_w, $q_{cat,w}$, τ_x, τ_y, τ_z, κ_w, ρ_e, P_e, T_e, $T_{v,e}$, $h_{0,e}$, u_e, v_e, w_e, M_e, μ_e, $c_{s,e}$, e_e, δ, δ^*, θ, Re_e, c_h (film coefficient), κ_e, k (roughness height), ρ_k, U_k, μ_k, Re_{kk}, and shock stand off distance

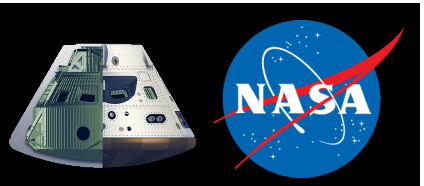
* Available at https://github.com/nasa/cfdtools

SAFEDB

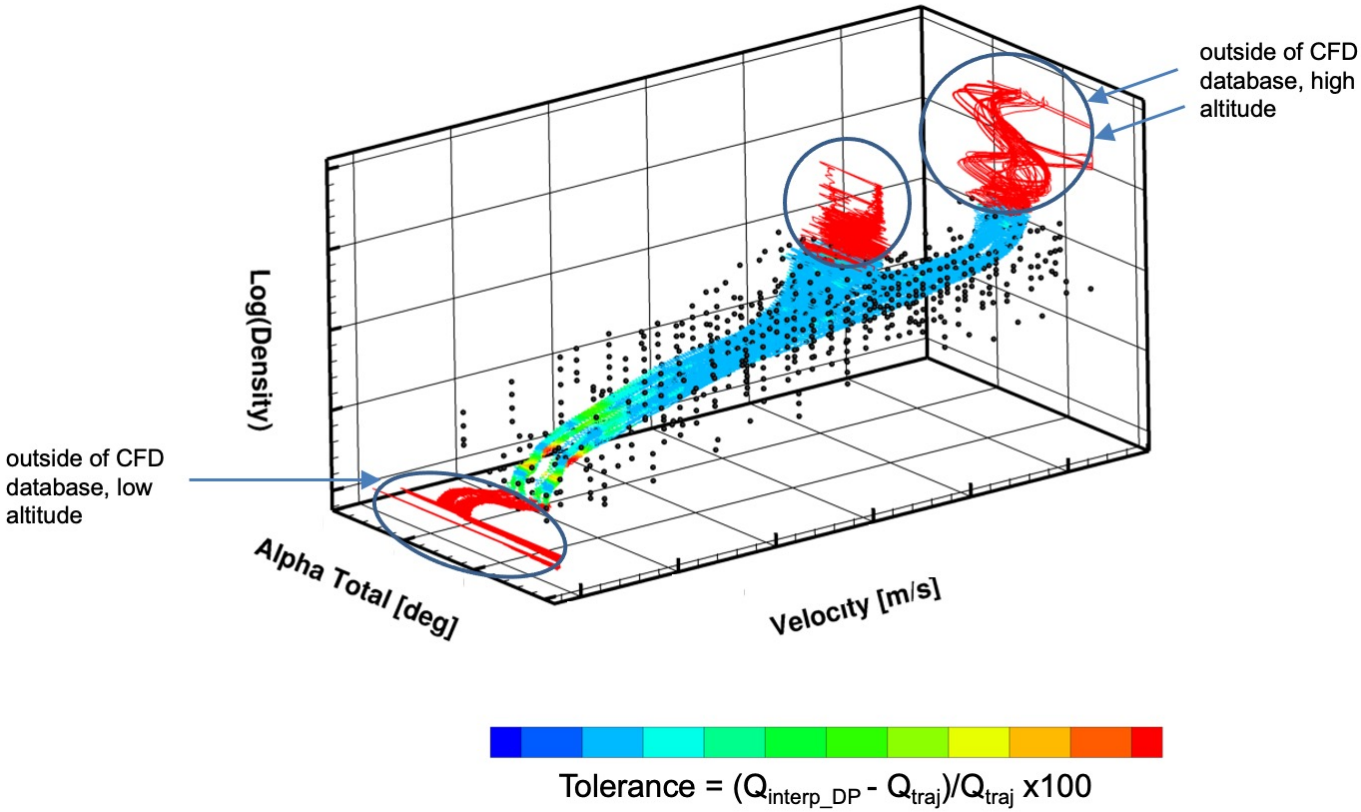


- **As number of cases grew beyond few hundred, manually maintain database became intractable**
- **System for Archiving Flight Environment DataBases (SAFEDB) is tool for managing ATDB files (grids, solutions, input files, QC files, file locations)**
- **Calculates hash for each file to verify integrity of database**
- **Python interface to SQLITE database**
  - Query database: “List all cases between 6 km/s and 7 km/s”
  - Execute user defined functions on entire database or subset of cases: “Extract q_w at x,y,z for all cases between 6 km/s and 7 km/s”
  - Package database for use with other analysis tools
  - Perform database quality checks

Database Quality Assessment: Laminar FC



- How do you know database resolution is fine enough for accurate interpolation?
- Heating indicator, $Q_{traj} = \rho^{0.5}V^3$, computed at every time point along trajectory
- Heating indicator then computed at CFD points
- Stencil of Q values at CFD points used to reconstruct value at every trajectory time point, Q_{interp_DB}
- % diff of Q_{traj} and Q_{interp_DB} gives measure of interpolation quality

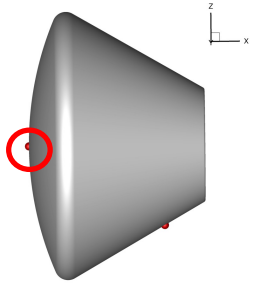


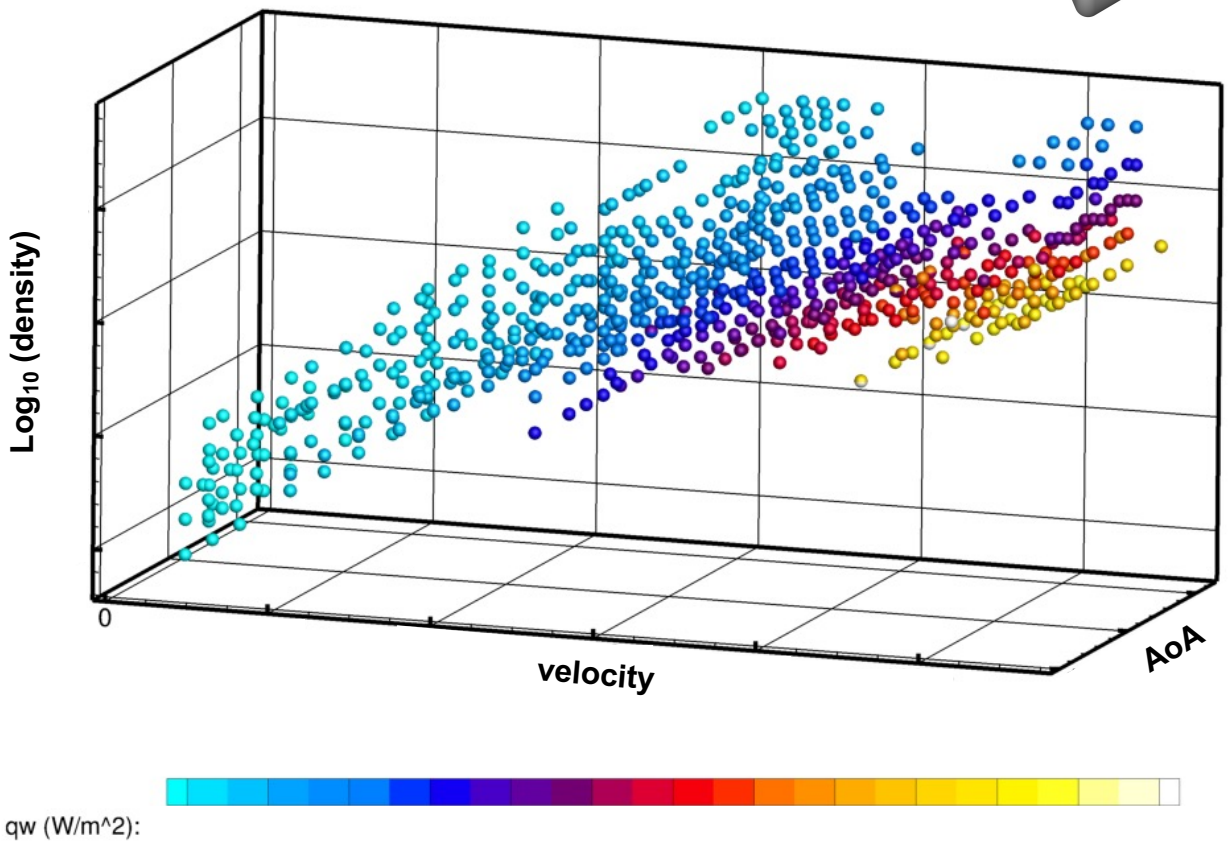
Convective Heating Check: Laminar FC

- No anomalies in solution trends detected.

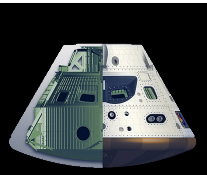
Laminar Fully Catalytic

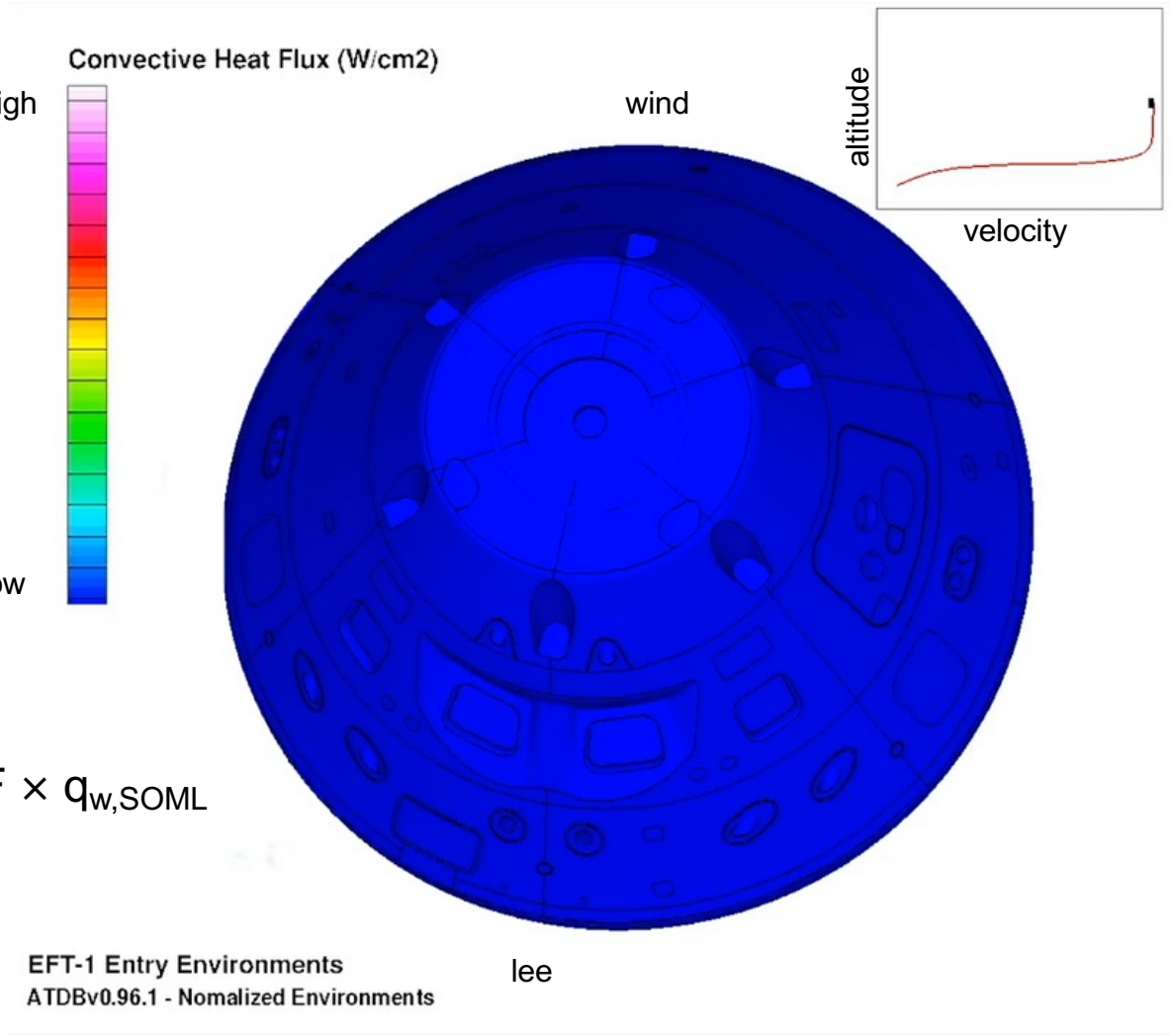
Center Point of Heatshield





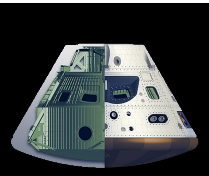
ATDB Simulation of EFT-1 Entry





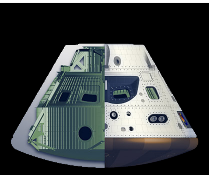
$q_{w,feature} = AF \times q_{w,SOML}$

Lessons Learned

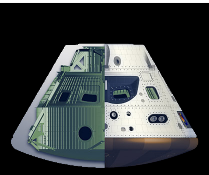


- **For "production scale" CFD, automation is essential**
- **Qual check solutions as a group**
- **Implement database management**
- **Continually reevaluate your best practices**
- **Archive solutions regularly in multiple locations if possible**
- **Check database quality at every stage (individual CFD cases, compiled cases, final implementation)**
- **Boundary layer edge detection**
  - Traditional 99.5% method of locating boundary layer edge is not robust enough for complex flows (expansion on after body, cross flow, etc)
  - Surface curvature method with 98% cutoff produces cleaner boundary layer height predictions
- **Full body solutions method**
  - If full body solution is initialized with mirrored half body flow field, it takes a long time for symmetric solution to break down
  - Starting full body solution from scratch is preferable

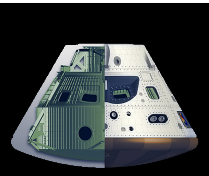
Questions



Backup



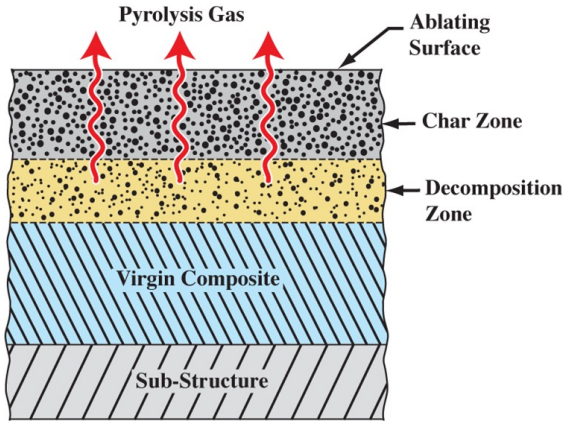
Heatshield Thermal Sizing Process

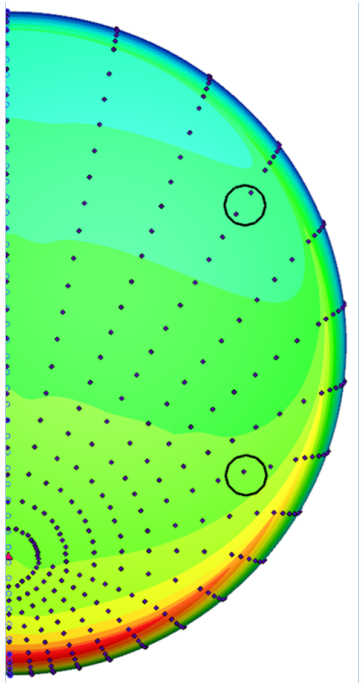


- **The block architecture presents challenges due to the presence of fencing/gapping at the block interfaces**
  - Molded Avcoat and RTV ablate at different rates resulting in fences or gaps depending on the heating environment
  - Fencing and gapping is a highly coupled process between the material and environments
    - Environment is dependent on time-varying feature geometry, primarily influencing heating augmentation and turbulent transition
    - Transition tripping introduces another coupling by linking downstream environments to upstream response
- **A two phased approach was developed to address the sizing**
  - Phase I provides a sizing of the block heatshield using arc jet test derived fencing profiles for limited environments (currently in use)
  - Phase II provides improved sizing of the block heatshield using a model based approach (still in-work)
    - Direct predictive approach of the differential recession between the block and gap filler materials which can augment the downstream environments
    - Models will evaluate the heatshield from the stagnation point and progress through downstream locations to capture the effects of fencing

Molded Avcoat Thermal Response Model

- **Developed a material response model for molded Avcoat**
  - CHarring Ablator Response (CHAR) code used for HS analyses
    - Finite element code that solves the energy and mass transport equations for pyrolyzing ablative materials
  - Utilized basic thermal property testing on virgin and charred molded Avcoat (e.g. TGA, thermal conductivity, specific heat, elemental analysis, etc.)
  - Aerotherm Chemical Equilibrium code used to extend the basic properties to derive pyrolysis gas properties and normalized surface recession tables
- **Material models anchored to arc jet test results over a wide range of test conditions based on recession and in-depth temperature performance**
- **All of the sizing analyses use 1-D models**
  - Some work has been completed to implement the multi-dimensional analysis capability

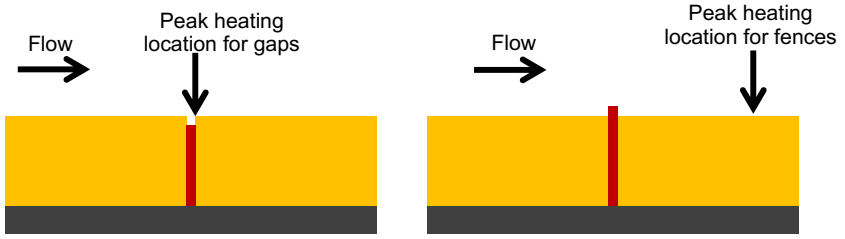




Avcoat Block System / Environment Interaction

The Block System Interacts with, is affected by, and affects the Environment

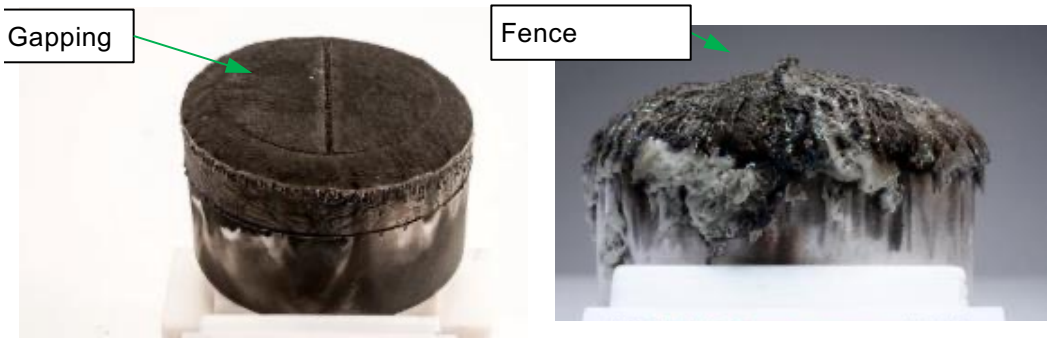
- **Fencing is a highly coupled process**
  - Feature formation/type is dependent on heating
    - High heat rates produce gaps
    - Low heat rates produce fences
  - Local environment is affected by seam features
    - Heating augmentation downstream of feature
    - Peak heating different for gaps vs. fences
  - Fences can induce transition, linking downstream environments to upstream response

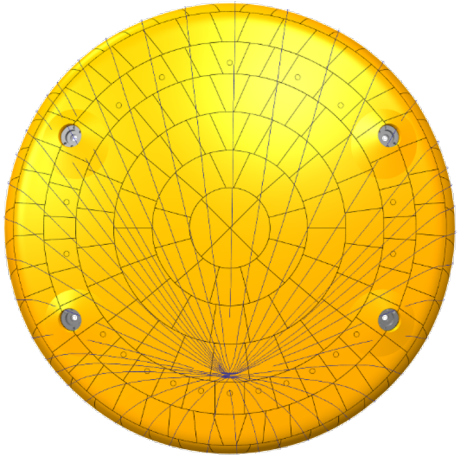


- **The peak heating location for fences and gaps occurs at different locations on the block and therefore sizing is run for both locations**
  - The worst case sizing from these 2 locations is used to size the acreage

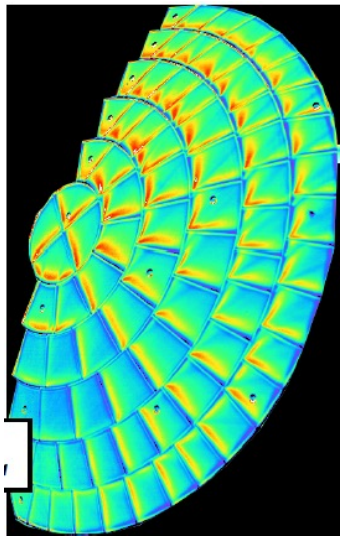
High Heat flux

Low-med Heat flux





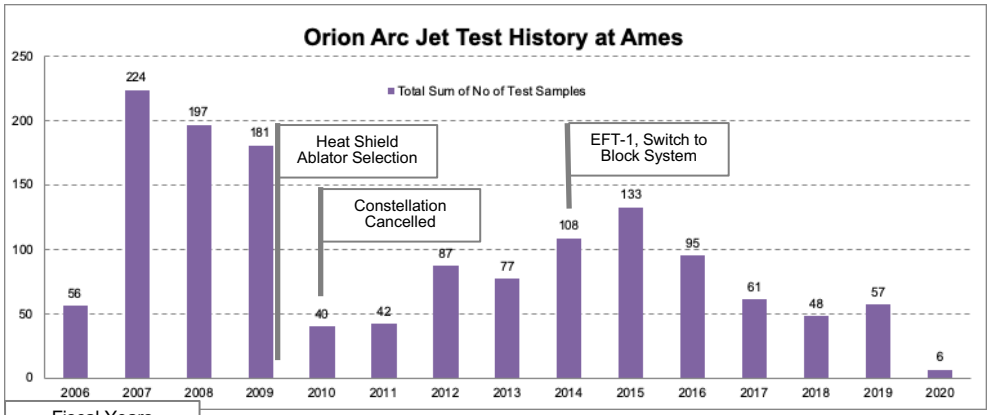
Streamline Overlay

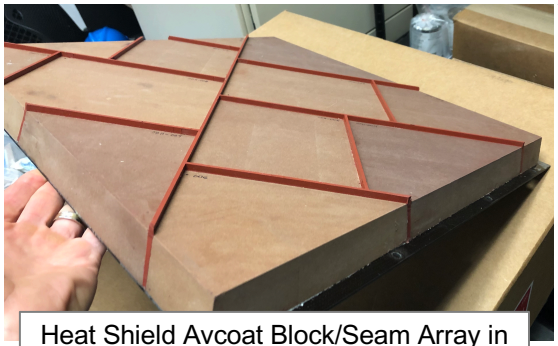


Wind Tunnel Test

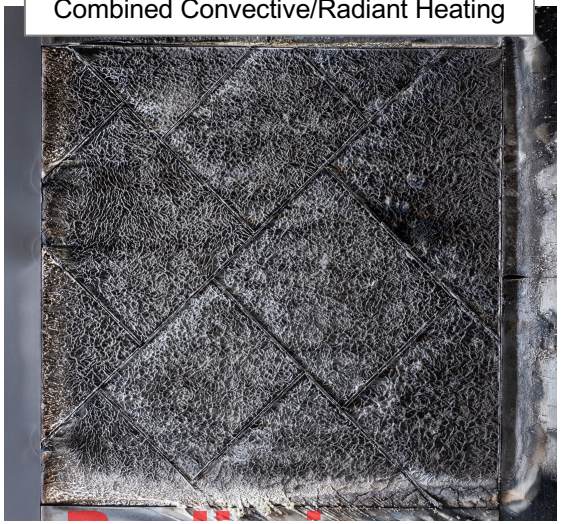
Orion Arc Jet Test Summary

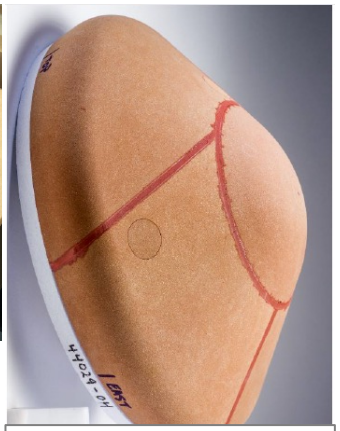
- **Since 2006, Orion has completed > 1,420 arc jet tests at NASA Ames Research Center**
  - Does not include arc jet tests at NASA JSC and the Arnold Engineering Development Center (AEDC) in Tennessee - another ~200 tests



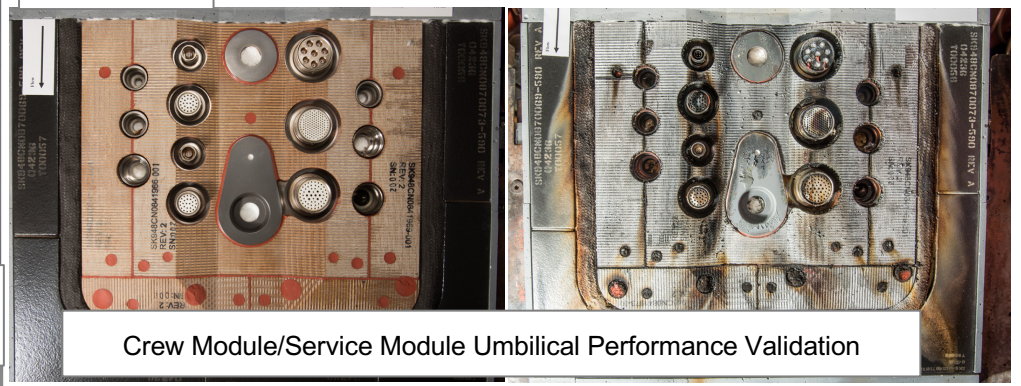


Heat Shield Avcoat Block/Seam Array in Combined Convective/Radiant Heating

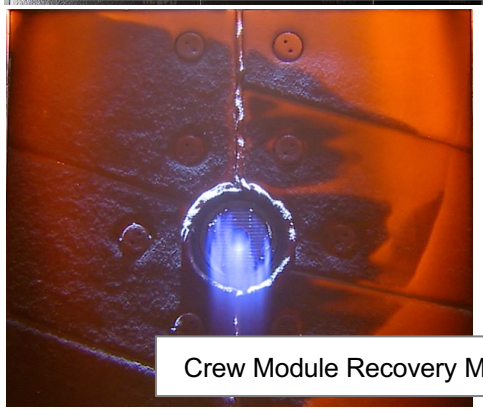




Heat Shield Seam Evaluations in High Heating Environments



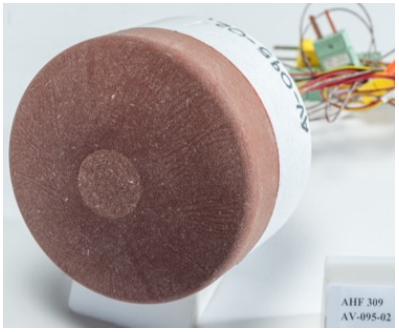
Crew Module/Service Module Umbilical Performance Validation

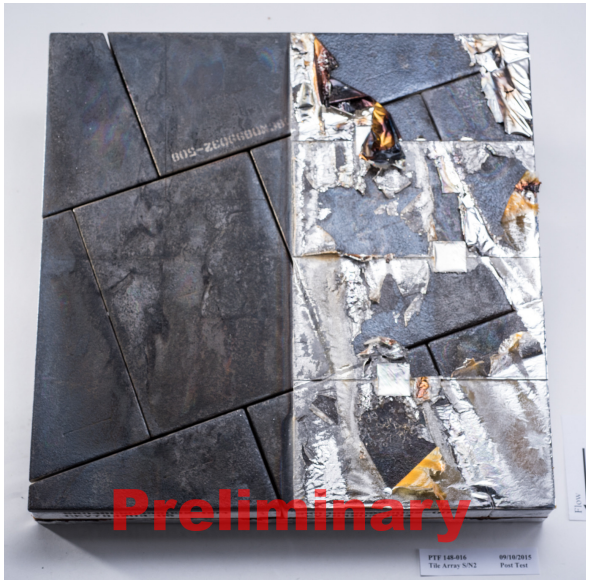


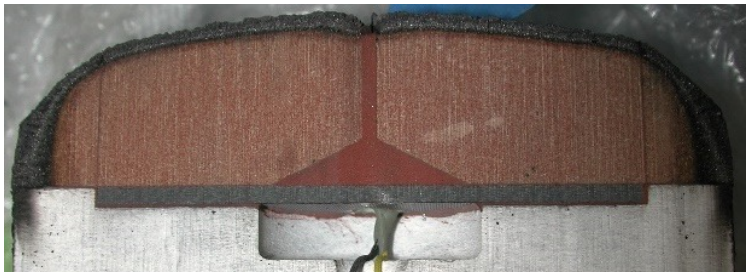
Crew Module Recovery Mechanism Hot Functional Testing

Arc Jet Testing - Why Do We Do It?

- **Material System Selection - what material systems will the spacecraft use?**
  - Orion selected Avcoat from amongst five different candidates, supported by arc jet testing
- **System Design - how will the Thermal Protection System (TPS) materials be installed on the spacecraft?**
  - Orion back shell tile and heat shield Avcoat block seam solutions were subject to arc jet testing
  - Surface coatings and thermal treatments were characterized in the arc jet
- **Material Qualification - are the materials being manufactured in a consistent way?**
  - Avcoat vendor changes and production line re-start events were accepted with the support of arc jet testing
- **Spacecraft Sustaining Engineering - is the system continuing to operate as expected?**
  - EFT-1 and Artemis-1 performance is confirmed with post-flight arc jet testing

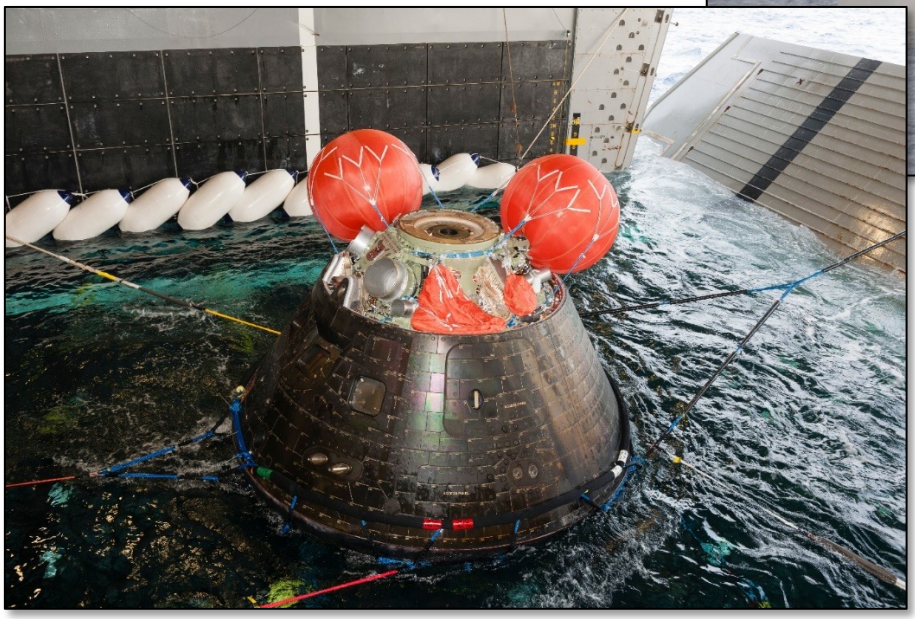


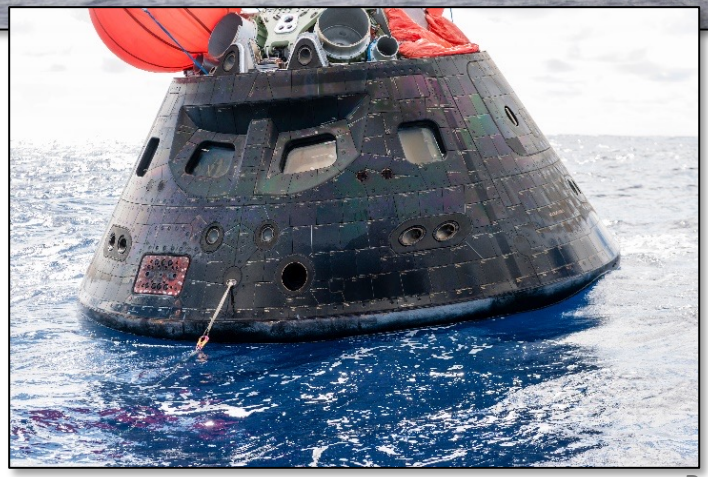




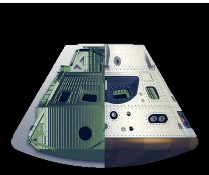
Arc Jet Testing is No Substitute for Flying!

- **EFT-1 Recovery:**
- **Horse collar and tow line attached to CM**
- **CM towed to USS Anchorage**
- **Reeled into well deck, which was then drained**





Artemis I Mission Description



ARTEMIS I

The first uncrewed, integrated flight test of NASA's Orion spacecraft and Space Launch System rocket, launching from a modernized Kennedy spaceport

1 LAUNCH
SLS and Orion lift off from pad 39B at Kennedy Space Center

2 JETTISON ROCKET BOOSTERS
Solid rocket boosters separate

3 JETTISON LAUNCH ABORT SYSTEM (LAS)
The LAS is no longer needed, Orion could safely abort

4 CORE STAGE MAIN ENGINE CUT OFF (MECO) and separation

5 ENTER EARTH ORBIT
Perform the perigee raise maneuver

6 EARTH ORBIT
Systems check and solar panel adjustments

7 TRANS LUNAR INJECTION (TLI) BURN
Burn lasts for approximately 20 minutes

8 INTERIM CRYOGENIC PROPULSION STAGE (ICPS) SEPARATION
The ICPS has committed Orion to TLI

9 OUTBOUND TRANSIT
Requires several attitude maneuvers

10 OUTBOUND TRAJECTORY CORRECTION (OTC) BURNS
As necessary adjust trajectory for Lunar flyby to DRO

11 OUTBOUND POWERED FLYBY (OPF)
62 miles from the Moon; targets DRO insertion

Heliocentric Disposal precludes re-contact

12 ORBIT INSERTION
Enter Distant Retrograde Orbit for next 6-23 days

13 DISTANT RETROGRADE ORBIT (DRO)
Orbit Maintenance burns and solar panel adjustments; 38,000 nmi from the surface of the Moon

14 DRO DEPARTURE
Leave DRO and start return to Earth

15 RETURN POWER FLY-BY (RPF)
RPF burn prep and return coast to Earth initiated

16 RETURN TRANSIT
Return Trajectory Correction (RTC) burns as necessary to aim for Earth's atmosphere; travel time 3-11 days

17 FINAL RETURN TRAJECTORY CORRECTION (RTC) BURN
Precision targeting for Earth entry

18 ENTRY INTERFACE (EI)
Enter Earth's atmosphere

19 SPLASHDOWN
Pacific Ocean landing within view of the U.S. Navy recovery ships

A B C D
CUBESATS DEPLOY
ICPS deploys 13 CubeSats total

ARTEMIS

Launch — Earth Orbit — Trans Lunar — Lunar Orbit — Trans Earth — Earth Re-entry — Payload Orbit/Disposal

ARTEMIS I

Total distance traveled: 1.3 million miles – Mission duration: 26-42 days – Re-entry speed: 24,500 mph (Mach 32) – 13 CubeSats deployed